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© A FLUME STUDY OF ALLUVIAL
BED CONFIGURATIONS

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "A FLUME STUDY OF ALLUVIAL BED CONFIGURATIONS" submitted by Douglas Gerald Mutter in partial fulfillment of the requirements for the degree of Master of Science.

ABSTRACT

The development and behaviour of bed forms in alluvial channels was studied by analyzing the results of a series of laboratory flume tests.

A tilting flume with a sand bed was employed for a total of thirty-one runs. An analysis was subsequently performed to determine the relationships between the measured variables at conditions near the transition from one bed configuration to another.

The analysis resulted in the representations of bed-configuration boundaries upon two graphical relationships. The first relationship involved a densimetric form of the Froude number, the concentration of the bed-material discharge and the ratio of the average depth of flow to the median diameter of the bed-material particles. The second relationship was identical to the first with the exception of the Froude number which was replaced by the slope.

The results were then compared with existing methods of predicting bed configuration.

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SYMBOLS

b	- Channel width (ft.).
C	- Concentration of bed material discharge by weight of total discharge (parts per hundred thousand, ppht).
c	- Velocity of propagation of a bed wave (ft./sec.).
D_{fall}	- Fall diameter of bed material (mm. or ft.).
D_m	- Median diameter of the bed material (mm. or ft.).
FR'	- Densimetric form of Froude Number $FR' = \rho_f V^2/\gamma'_b h$
g	- Constant of gravitational acceleration (ft.^{2}/sec.).
h	- Average depth of flow (ft.).
q	- Average discharge per foot of channel width (cfs/ft.).
Q	- Discharge of water-sediment mixture (cfs).
S	- Slope of the energy-grade line equal to the slope of the water surface or the bed slope during equilibrium conditions.
V	- Average velocity according to the continuity principle (ft./sec.).
X	- Variable describing physical characteristics of the bed material (gradation, particle shape, etc.).
V_i	- Dimensionless parameter $V_i = \frac{\sqrt[3]{\nu g}\quad D_{50}}{\nu}$
γ'_b	- Buoyant unit weight of the bed material (lb./ft.^{3}). $\gamma'_b = g\,(\rho_b - \rho_f)$.
Δ	- Height of bed wave (ft.).
λ	- Length of bed wave (ft.).
ν	- Kinematic viscosity of water-sediment mixture (ft.^{2}/sec.).
ρ_b	- Density of bed material particles (slugs/ft.^{3}).
ρ_f	- Density of the fluid (slugs/ft.^{3}).
τ_o	- Shear stress acting on the bed (lb./ft.^{2}).
ω	- Fall velocity of bed-material particles (ft./sec.).

CHAPTER I

INTRODUCTION

1-1 General

Alluvial channels, which may be defined as being capable of forming their own boundaries by erosion, transport and deposition of sediment, have been used, modified and even created by man for centuries. However, with all his experience, man has not yet been able to understand the mechanism of these processes completely.

Because the fluid in alluvial channels has two constituents (water and sediment), the bed is characterized by various configurations which form according to the flow conditions. The determination of the rather ill-defined boundaries between different types of bed form is basic to the quantitative study of sediment transport and resistance to flow in alluvial channels.

Studies in the specific area of bed forms can be classified under two headings. The first is observation of the phenomenon (both in the field and in the laboratory) and the subsequent derivation of empirical formulas. The second is derivation of formulas from assumptions or theories. The latter method seems to have been less successful in describing the overall phenomenon.

Until recently, few experimenters noted the form of bed roughness at known flow conditions, so work under the first heading is relatively backward. Therefore, laboratory investigations are necessary to define, as completely as possible, the presently sketchy bed form phase boundaries.

1-2 Aim and Scope of Study

The object of this study has been to define more precisely the conditions at which transitions in bed form configuration occur, and to determine the extent of any transitional areas which may exist.

The experimental procedure consisted of the adjustment of any two flow parameters (primarily slope and depth) in such a manner as to approach the phase boundary with due attention to changes in bed form. The boundaries were approached from both sides to ensure the determination of transitional zones. Measurements were made of as many basic quantities as possible (including the bed form dimensions, velocity profiles, etc.). Although these measurements may not all be directly related to this particular thesis, they may provide data for later work without duplication of experimental efforts.

CHAPTER II

LITERATURE REVIEW

Probably the first attempt to determine an empirical formula to describe the movement of a bed form was that of Sainjon (ref. 4, p. 12). His studies on the Loire River in France led him to suggest that:

$$c = 0.00013\ (V_n^2 - 0.11) \tag{2-1}$$

where c is the velocity of propagation of a dune (metres/sec) and V_n is the velocity of water on the surface of the river. It is significant that this formula excludes the dune height and water depth.

In 1883 Darwin (ref. 6, p. 175) published the results of experiments on sand ripple formation due to oscillatory motion of water over the bed. He felt that ripple formation was due to the generation of vortices in a layer between two uniform streams (water and sand). However, the first documented flume study was performed by Deacon (ref. 4, p. 12) in 1892. This author related the formation of ripples to water velocity. The experiment extended to the plane bed stage, and excellent descriptions were made of the mechanism of ripple formation. The most extensive early flume tests were those of Gilbert and Murphy (ref. 6, p. 178) in 1914, and related slope, discharge and channel shape with sediment transport. Formation of all bed forms, including the antidune, was described.

Exner (ref. 6, p. 176) in 1932, employed a more analytical approach to the problem. He assumed that the capacity of water to transport sediment depends on velocity; therefore, acceleration results in scour and deceleration results in deposition. By assuming a uniform velocity distribution

and a sinusoidal bottom shape of wavelength λ and amplitude "a", Exner concluded that:

$$c_r = \frac{qK}{(y-\eta)^2} = \text{velocity of propagation of ripples, and} \quad (2\text{-}2)$$

$$\eta = A_o + A_1 \cos\alpha \left(x - \frac{qKt}{(y-\eta)^2} \right) = \text{bed elevation,} \quad (2\text{-}3)$$

where q is the discharge per unit width. The height of the bed is η and the height of the water surface is y (above some arbitrary datum). Although his theory does not indicate how the sinusoidal form is generated from a plane bed, it does explain the transformation from sinusoid to an asymmetric wave with a gentle upstream slope. Figure 2-1 is an illustration of Exner's mathematically derived dune profile. Exner further considered water surface slope and friction and derived complex relations for bed-form shape and channel width.

In 1934 Kramer (ref. 4, p. 16) employed flume tests to determine the range of conditions for which a certain sand was suitable for hydraulic model tests. Rather than relating bed formation directly to velocity, as was the custom previously, Kramer used tractive force per unit area on the bed (or boundary shear) as a parameter. He concluded that the range's lower limit (formation of ripples) is dependent on the tractive force and the size and gradation of the bed material; the upper limit (formation of dunes) is dependent, in addition, on the hydraulic slope. In the ensuing discussion on Kramer's paper, Straub (ref. 6, p. 178) in 1935, concluded that initial movement and development of bedforms is dependent on the Froude number, gradation, and tractive force. Straub's experiments indicated that the height and sharpness of bed forms reaches a maximum at the critical

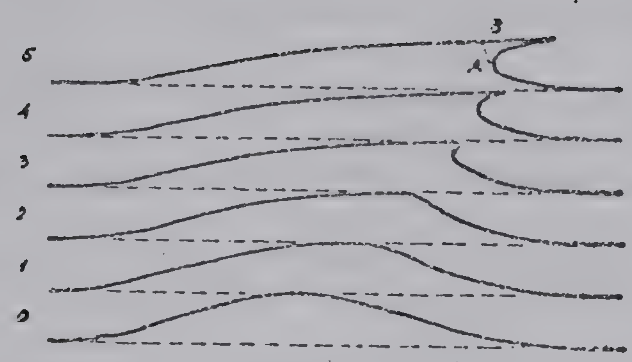


FIG. 2-1. EXNER'S MATHEMATICALLY DERIVED DUNE PROFILE

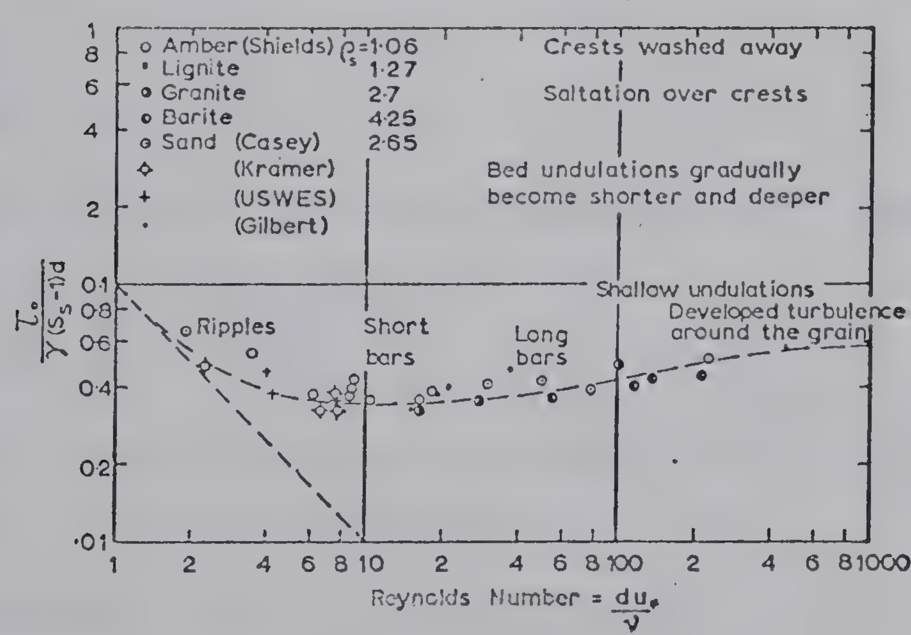


FIG. 2-2. SHIELDS DIAGRAM

energy of flow and decreases as the energy increases. He also noted that the length of ripples is much less sensitive to changes in flow conditions.

Shields, in 1936, investigated the development of bed forms. The graphical representation of his work (ref. 6, p. 101) has become known as the Shields diagram (see Figure 2-2). Shields concluded that bed formation was mainly controlled by $\frac{\tau_c}{\gamma' d}$ where τ_c is the critical drag, γ' is the submerged particle density and d is the grain diameter, and by $\frac{d}{\delta}$ where δ is the thickness of the laminar film.

Goncharov (ref. 6, p. 179) defines bed formation in terms of some non-transporting velocity (V_{non}) and a relative roughness $\left(\frac{K}{Y_o}\right)$. The velocity at which bed forms begin to develop is V' where:

$$\frac{V'}{V_{NON}} = 2.5\left(\frac{K}{Y_o}\right)^{1/12} \tag{2-4}$$

The velocity at which bed forms disappear is V''' where:

$$\frac{V'''}{V_{NON}} = 2.5\left(\frac{Y_o}{k}\right)^{1/12} \tag{2-5}$$

The velocity at which maximum development occurs is V'' where:

$$V'' = 0.75\ V''' + 0.25\ V'. \tag{2-6}$$

Bakhmeteff (ref. 4, p. 15) involved the use of the "kinetic flow factor" (square of the Froude number) which resulted in expressions for the velocity of propagation of bed forms such as:

$$\frac{C_r}{V} = 0.0188\ \frac{V^2}{gY_o} - 0.0292\ \frac{gd}{V^2} \tag{2-7}$$

Velikanov's work (ref. 6, p. 181) in 1936, was mainly concerned with the structure of turbulence in open channel flow. He proposed a mathematical model explaining that turbulence (in the form of large scale periodic eddies) could cause scour and deposition on the bed. Furthermore, he was able to show that the generation of a sinusoidal bed form from a plane bed (a basic assumption in Exner's development) could be determined from turbulence considerations. Similar work was performed by Tison (ref. 6, p. 184) who, in addition, concluded that periodic ripples do not occur in the laminar flow of a highly viscous fluid.

Ismail (ref. 4, p. 20) studied flow in a closed conduit with bed forms, using Reynold's number as a criterion for ripple formation. He concluded that some critical Re exists, below which part of the sediment moves as bed load, and above which all sand moves in suspension (dunes are swept away).

Anderson, Kondrat'ev and Kennedy (ref. 6, p. 184) all considered the problem in terms of potential flow. Kennedy derived a complicated analytical solution which contains an unknown dimensionless parameter that is dependent on depth and velocity of flow and the fluid and sediment properties. As such, his approach adds little to the overall understanding of the problem.

Most recent work is in terms of the Froude number (in some form), as illustrated by Figure 2-3 from the work of Simons and Richardson (7). Subsequent work by these authors (10) relates the phases of bed forms to stream power ($\tau_o V$) and median fall diameter of the bed material. This relationship is shown graphically in Figure 2-4. This analysis employed both flume and field data and was intended to facilitate the prediction

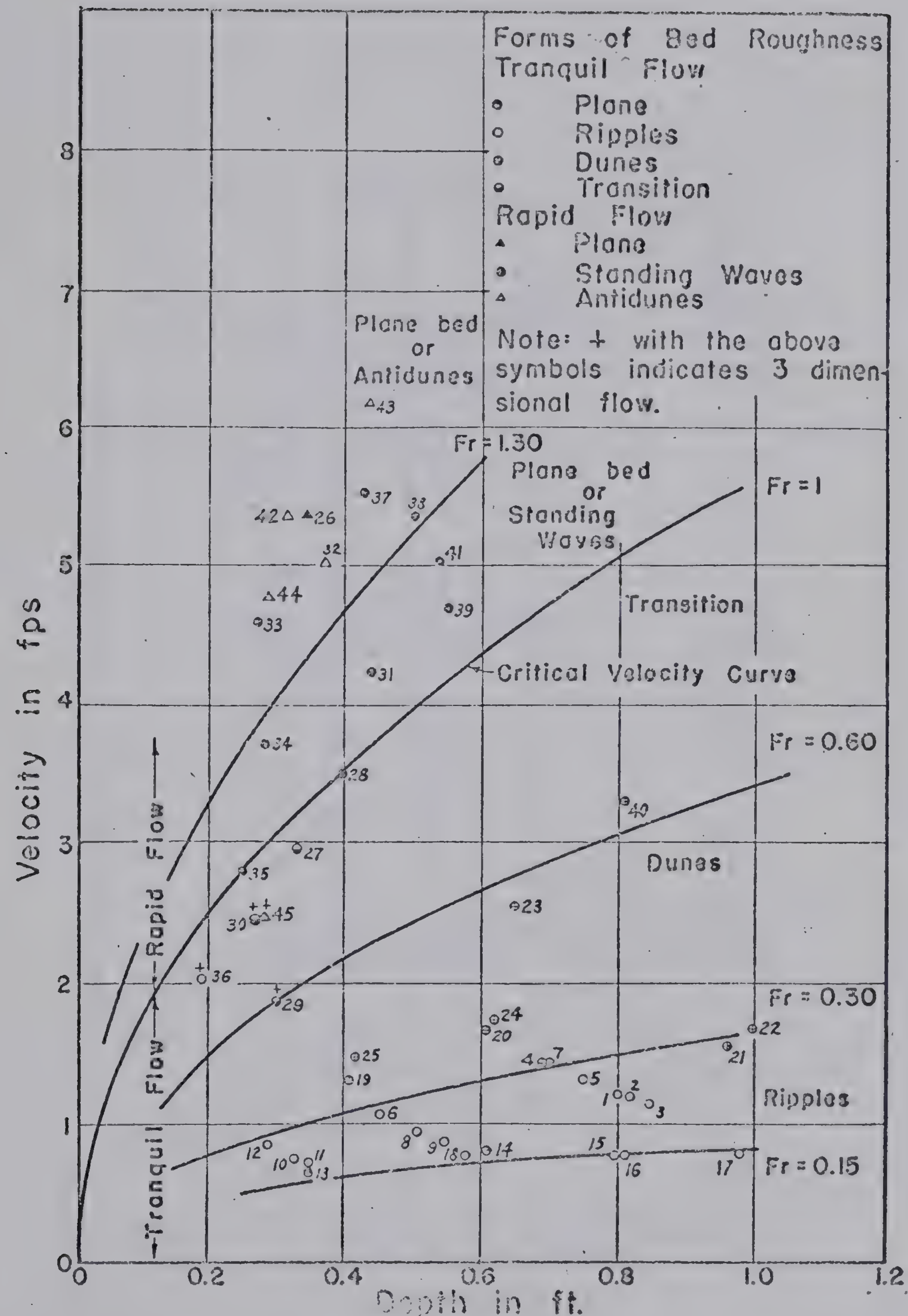


FIG. 2-3. SIMONS AND RICHARDSON CRITERION FOR PREDICTING BED CONFIGURATION

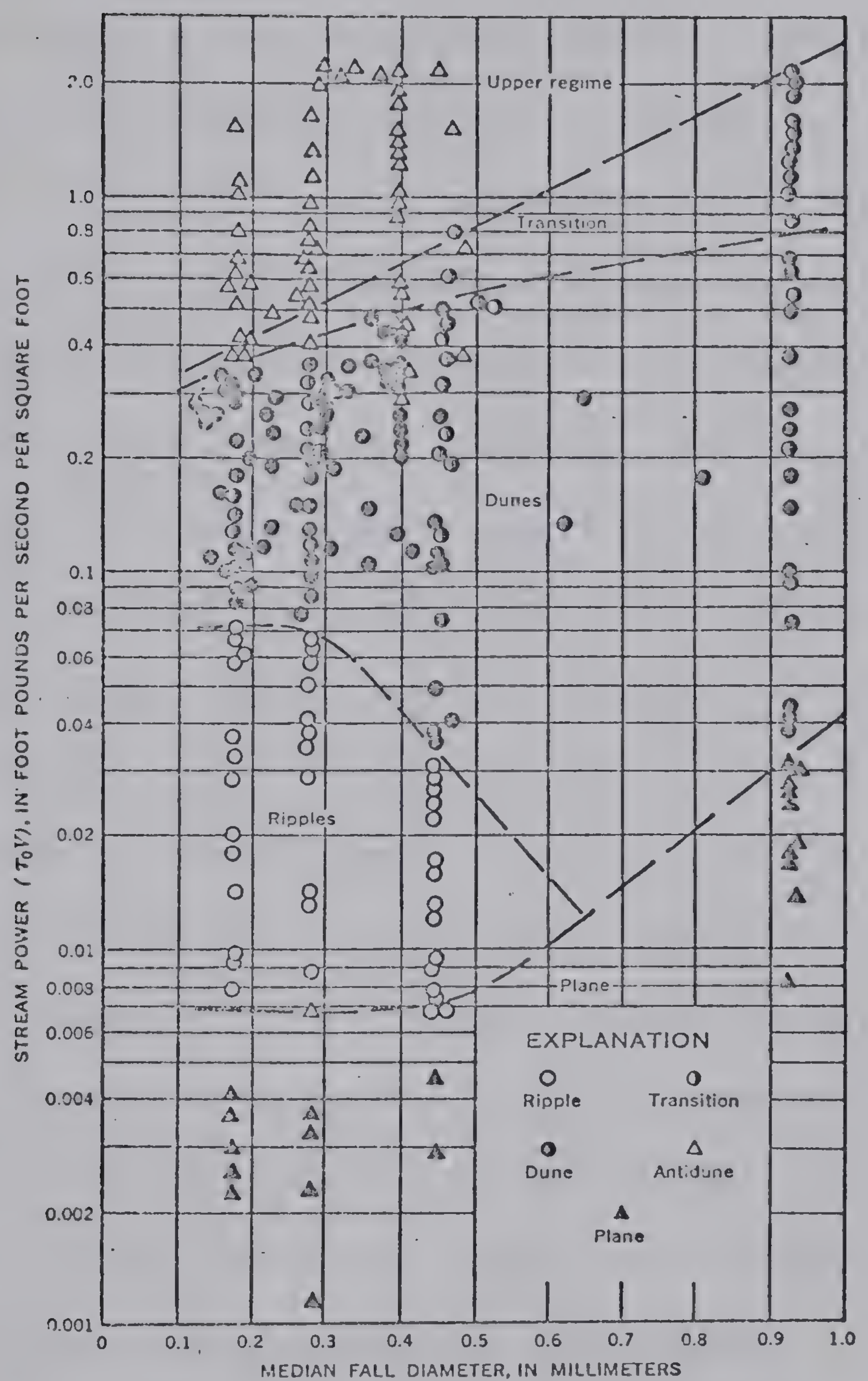


FIG. 2-4. SIMONS AND RICHARDSON CRITERION FOR PREDICTION OF BED FORMS

of the form of bed roughness, given slope, depth, velocity and fall diameter.

Dimensional analysis led Liu (5) to the use of a Reynolds number as a parameter in defining the various phases of bed forms. A comparison of Liu's criterion for ripple formation, Shield's initiation of motion curve and the Simons and Richardson curves was published by the last authors (8) in 1961. It is presented graphically in Figure 2-5. After discussion of Liu's paper had concluded, the author was of the opinion that ripple formation was caused primarily by an interaction of turbulence and instability of the sand-water interface. However, Vanoni and Brooks (12) felt that the consideration of stratified flow was inappropriate as the sand layer of "flow" has many characteristics which differ from those of a very dense fluid. Many subsequent analyses have been made with reference to turbulence, but due to their complex nature and inherent assumptions, they remain rather academic.

Cooper (3), in an analysis of world flume data, indicate the phase boundaries on general solution surfaces for coordinates of Fr', C, h/D, and S, C, h/D. This more general, dimensional approach is more likely to result in a basic understanding of the problem. Their study reveals areas in which flume studies have not provided sufficient information and in which future efforts should be concentrated.

The problem of identifying and classifying the physical features of bed forms is not nearly as controversial a subject as is the prediction of the form of roughness for a given flow condition. The classification system proposed by Simons and Richardson (7) has been generally accepted. Yalin (13) suggested that ripples and dunes share a geometric resemblance

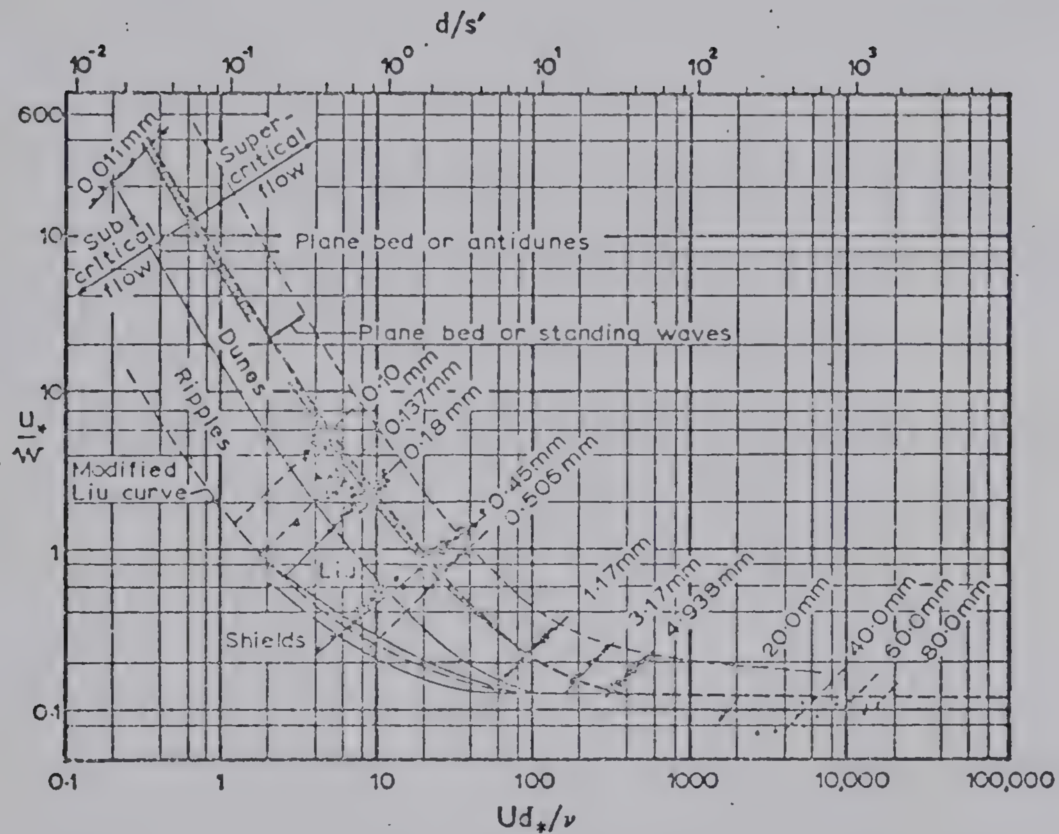


FIG. 2-5. SIMONS, RICHARDSON AND ALBERTSON CRITERION FOR PREDICTING BED CONFIGURATION

but that ripple size depends on grain size (not flow depth) whereas dune size depends largely on the depth of flow (and is independent of grain diameter). Simons and Richardson also indicate that the length of these bed forms is much less sensitive to changes in flow condition than is the height.

CHAPTER III

EXPERIMENTAL PROGRAM

3-1 Objective and Scope of Study

As stated briefly in the first chapter, the objects of this study were to define the conditions at which transitions in bed configuration occur, and to determine the nature of any transitional configurations which may exist.

The experimental approach used in pursuing these objectives was to slowly change the slope and depth (to maintain uniform flow conditions) while keeping discharge constant. According to existing knowledge, the sequence of bed configurations which could be expected for increasing slopes (and decreasing depths) was: (1) ripples; (2) dunes; (3) upper flow regime. A sequence of bed configurations in the reverse of that stated above could be expected to result from decreasing the slope (hence increasing the depth). Upon commencement of transition from one bed to another, the flow conditions were allowed to stabilize and measurements were taken. Attempts were made to develop bed configurations according to both the sequences mentioned above, so as to determine the existence of any transitional bed forms and to determine the possible effects of antecedent bed forms on the development of the new configuration.

However, the physical nature of the laboratory apparatus imposed some limitations on the experimental range of slopes and depths which could be achieved. This became critical in the case of high slopes as discharge was limited to approximately one cfs, and at lower discharges meandering tended to occur within the flume's four foot width. Thus, a

lack of testing resulted in the upper regime area (specifically, in defining the upper boundary of the transition from dunes to upper regime).

3-2 Apparatus

While the aforementioned limitations did exist, the experimental apparatus provided a sufficient range of adjustment to allow attainment of the basic objectives of this study.

The flume (which is illustrated in Plates 3-1 and 3-2, and in the schematic diagram of Figure 3-1) is located in the Graduate Hydraulics Laboratory of the University of Alberta. It has a width of four feet and a length of one hundred feet (although the use of baffles and a wave suppressor reduced the effective length to eighty-six feet). The entire water-sediment mixture was recirculated through one of two return lines. Gate valves regulated the flow so that at higher discharges a four inch diameter return line was used, while at lower discharge a two inch diameter line was employed. This procedure kept the velocities in the return lines high enough to prevent the development of bed forms (due to deposition of suspended material) which could have reacted to any changes in the flow conditions. As a further precaution against external disturbances to the system, a baffle was installed at the outlet of the return line to reduce the turbulence at the entrance to the flume and a wave suppressor was employed to reduce wave action at higher discharges. The material used to pack the baffle was aluminum shavings which effectively reduced turbulence and resisted corrosion.

The water-sediment mixture was recirculated by means of a Wilfley sand pump which had a maximum discharge of approximately one cfs. It was capable of pumping a slurry of up to 80% sand, a feature which became of

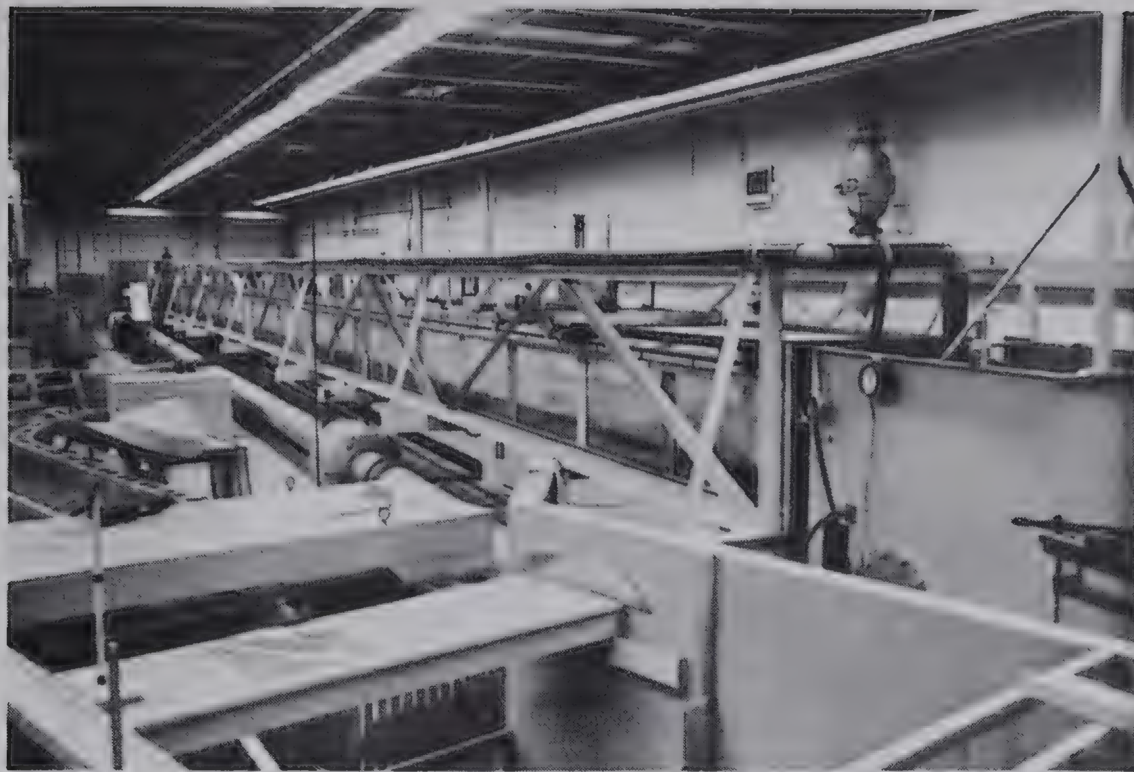


PLATE 3 - I. THE EXPERIMENTAL FLUME

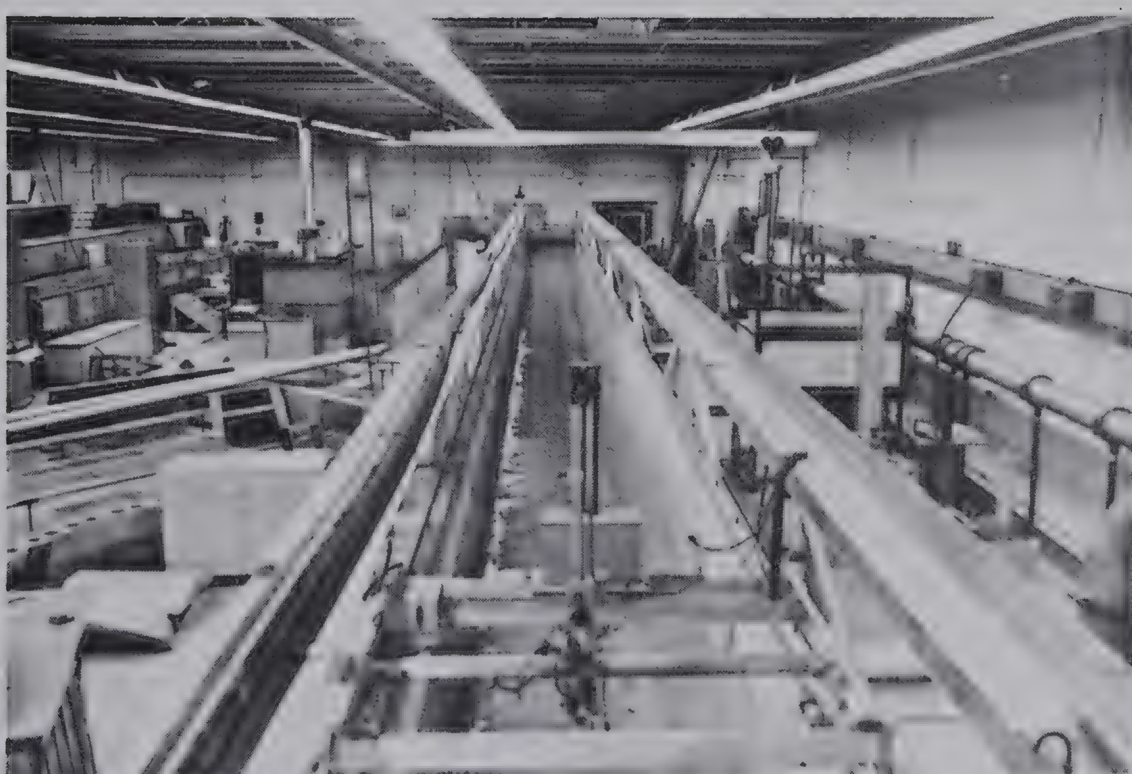


PLATE 3 - 2. THE EXPERIMENTAL FLUME

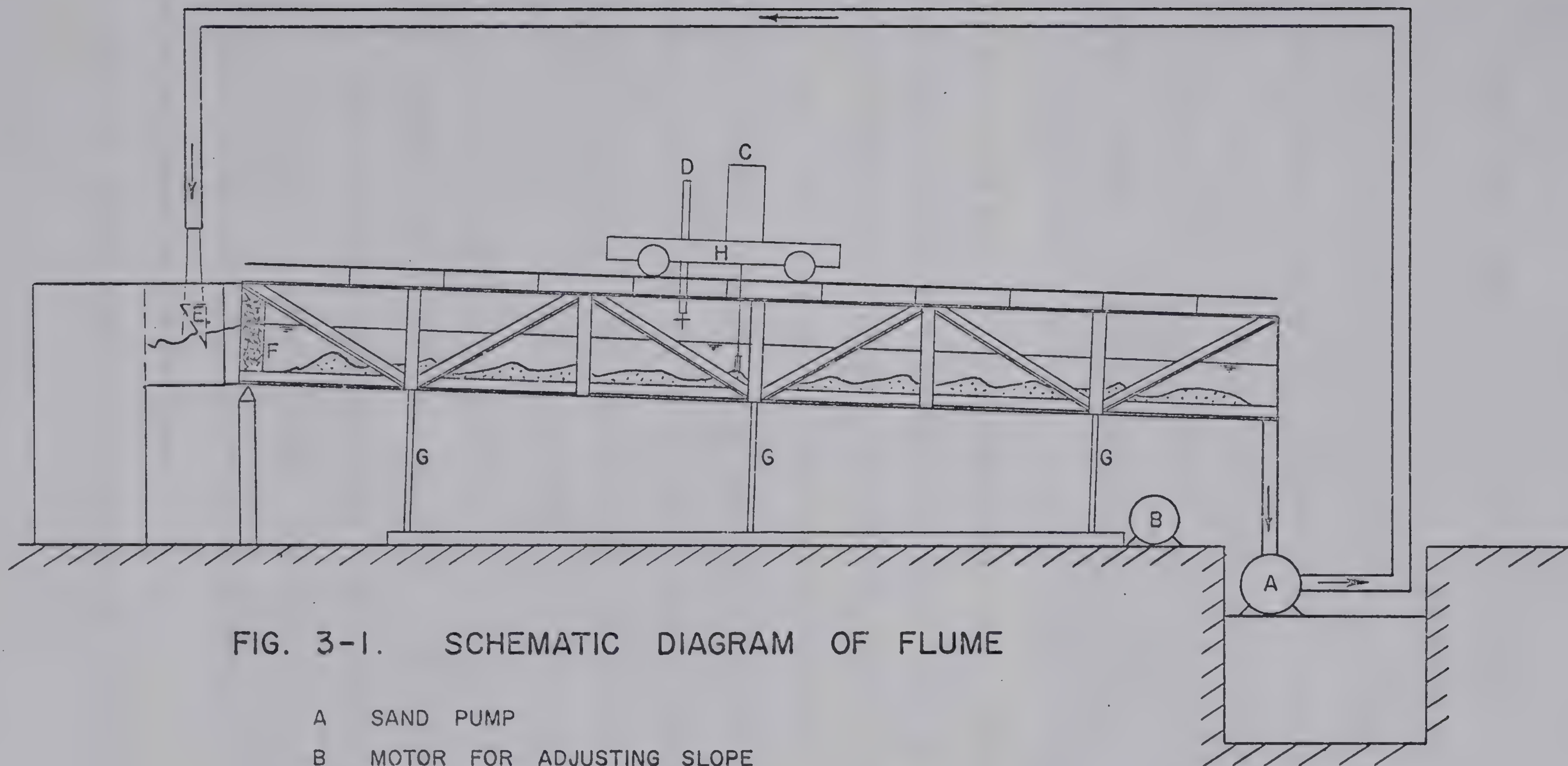


FIG. 3-1. SCHEMATIC DIAGRAM OF FLUME

A SAND PUMP
B MOTOR FOR ADJUSTING SLOPE
C BED PLOTTER
D VELOCITY PROBE
E SLICE SAMPLER
F BAFFLE
G JACKING MECHANISM

use when the flume was refilled with water (causing bed material to slump into the inlet to the pump).

The discharge was determined by means of a Foxboro magnetic flow meter and chart recorder. The device had two calibrated channels, one of which read from zero to one cfs, the other of which read from zero to twenty cfs. The flow meter (shown in Plate 3-3) was installed vertically to eliminate air pockets or sediment deposition near the electrodes.

Plate 3-4 shows the manometer board which was employed to determine the water surface elevation above pressure taps located every ten feet along the centerline of the flume bed. Plastic tubing ran from each tap to the board, which had an infinitely adjustable slope. The system was flushed periodically with water from the city mains so as to purge the lines of any air bubbles which could affect the manometer readings.

As the entire water-sediment mixture was recirculated, it was desirable to take a total load sample at the outlet of the return line. This was accomplished with the use of a slice sampler. This device was mounted on a threaded shaft which, when rotated, caused the sampler to traverse the flow as it exited the return line vertically downwards. It was designed to collect a sample of approximately five hundred ml (depending on the cranking speed and water velocity). An enlarged bottom portion of the sampler was designed to act as a reservoir to prevent overflow due to the high entry velocities. The width of the opening was made several times larger than the median grain diameter to prevent sediment from becoming lodged in the entrance.

The dimensions of bed forms and the slope of the bed relative to

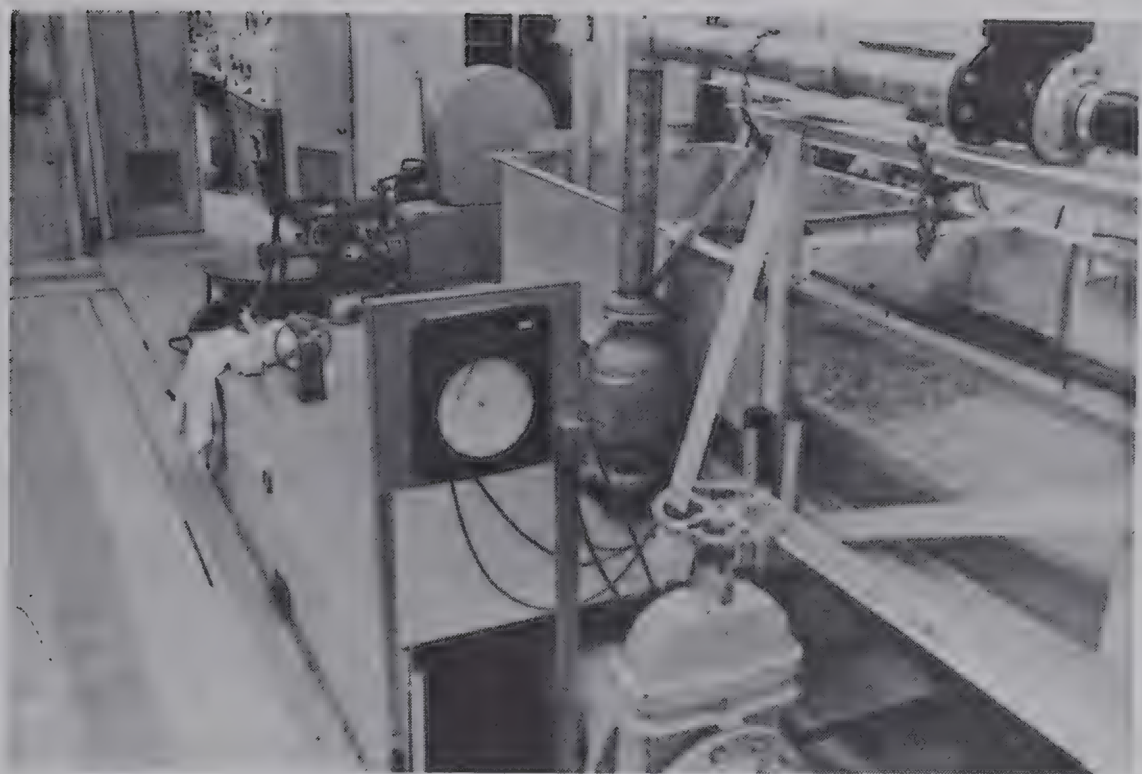


PLATE 3-3. MAGNETIC FLOW METER AND CHART RECORDER

PLATE 3-4. MANOMETER BOARD

the flume bottom were determined by the bed plotter shown in Plates 3-5 and 3-6. This device consisted of a probe which was controlled so that it remained at a constant distance from the bed while the carriage upon which it was mounted traversed the length of the flume on rails parallel to the flume bed. The head of the probe contained an active electrode, at the bottom tip, and a remote grounded electrode. When the tip of the probe approached a non-conductor (such as the sand bed) the impedance between the two electrodes increased. This change in impedance caused a servo motor to restore the original separation between the probe and the bed. The movements of the probe and the carriage were monitored by potentiometers which caused the bed profile to be recorded on an X-Y plotter.

A Sanborn velocity probe was also mounted on the carriage mentioned above. It was used to obtain velocity profiles at the centerline and third points of a cross-section during the run. However, due to the nature of the probe, the lowest point on the profile was 0.03 feet above the bed and the highest point was 0.03 feet below the water surface. For this reason velocity profiles were not recorded for runs with shallow depths (less than about 0.2 feet).

The bed material, while actually being one of the variables of the study, remained the same for all the tests, so it will be considered as having been part of the apparatus. The bed was comprised of Selkirk sand with a specific gravity of 2.65 and median diameter of 0.26 mm. The grain size distribution of this material is shown in Figure 3-2.

3-2 Procedure for Determining Slope and Depth

Due to the existence of bed forms on the bed, it was necessary to develop a reliable means of measuring depth and slope. It was

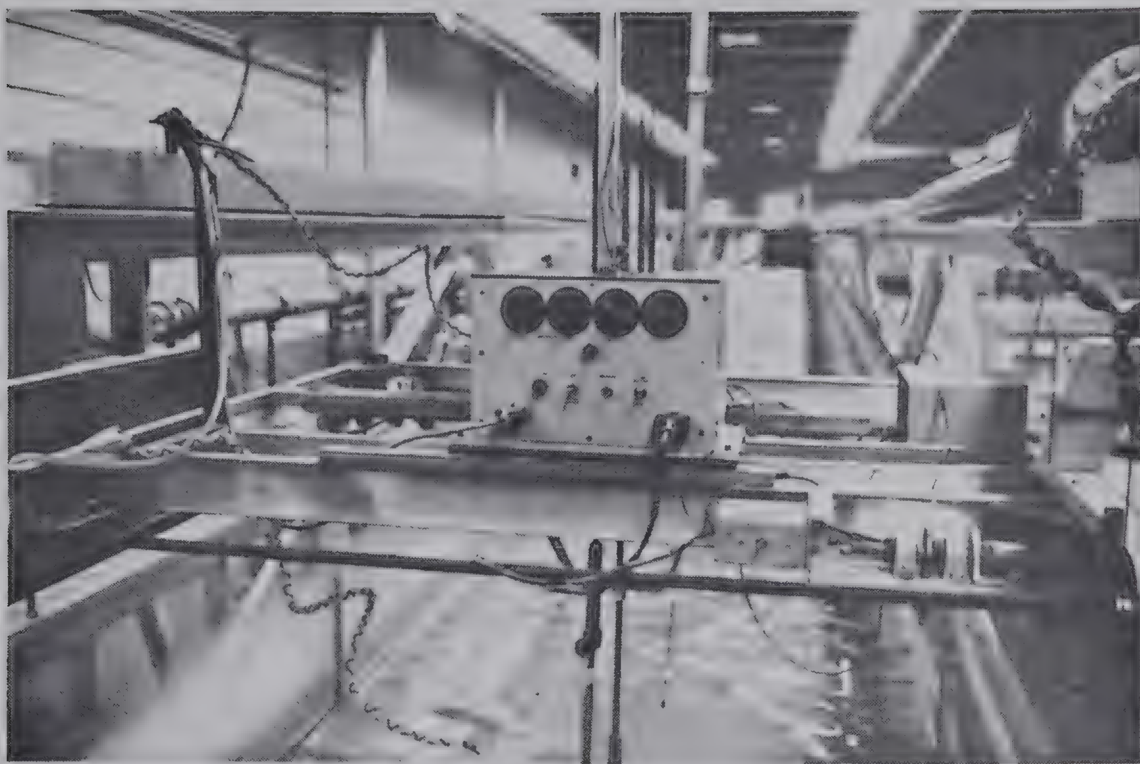


PLATE 3 - 5. BED PLOTTER AND CARRIAGE

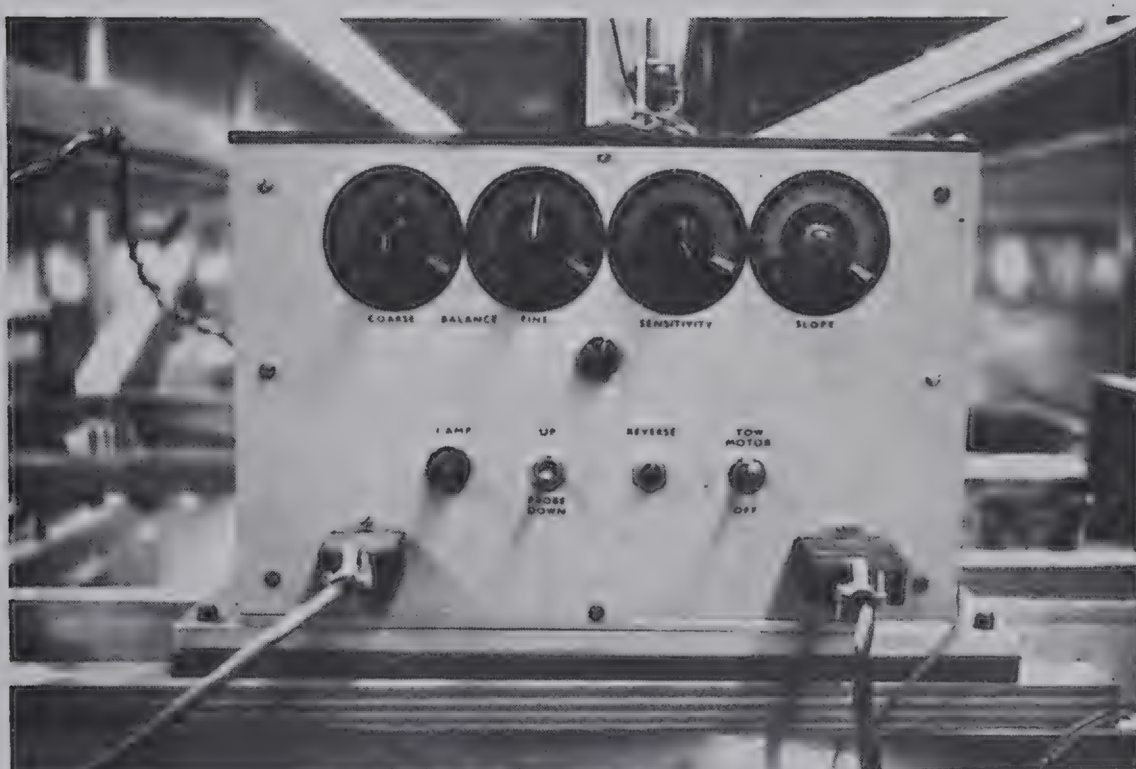


PLATE 3 - 6. BED PLOTTER CONTROLS

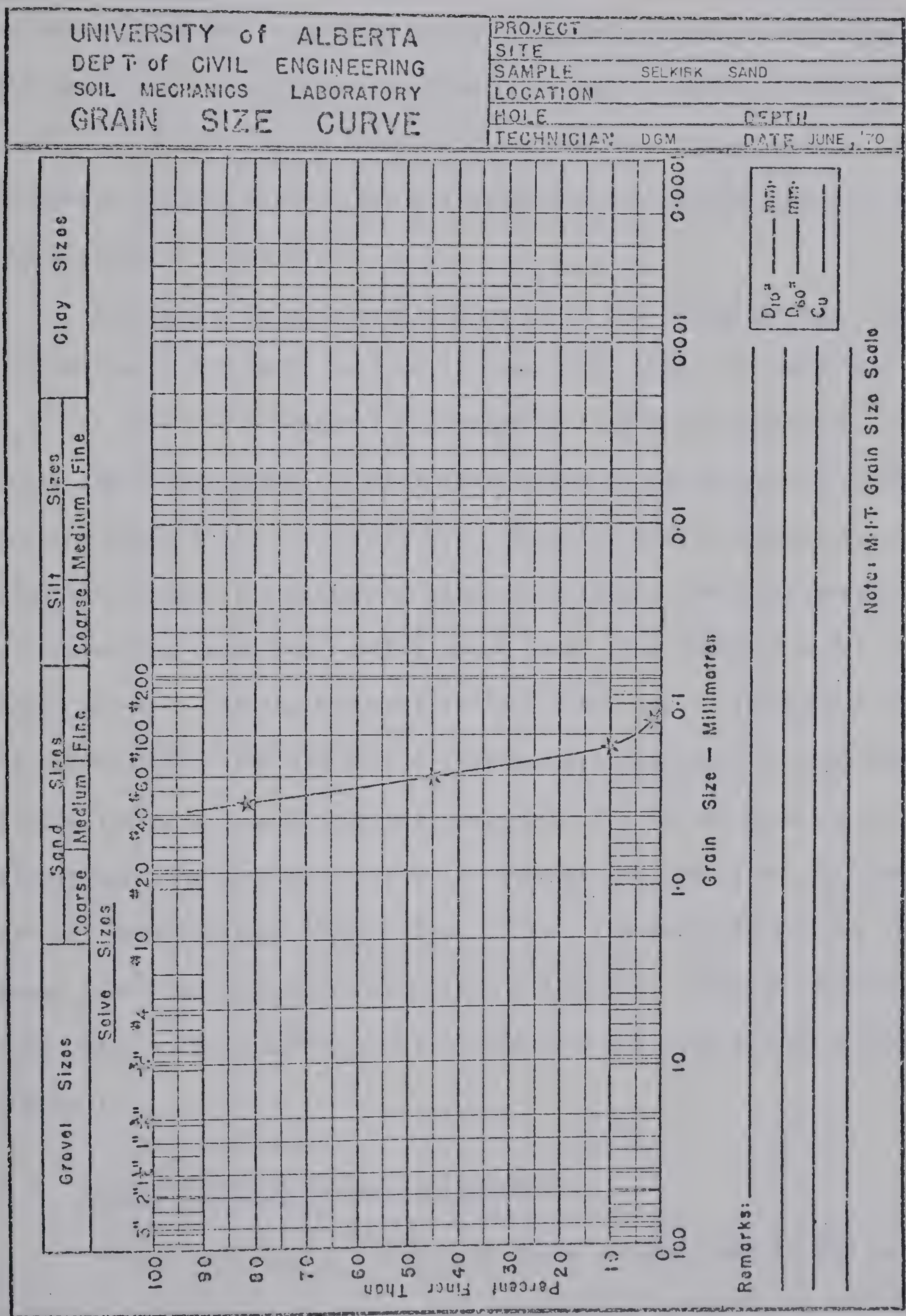


FIGURE 3-2. GRAIN SIZE CURVE

impossible, because of the undulations in the bed, to measure h and S over a short reach while the run was in progress. Furthermore, in order to prevent the bed forms from being swept away at the termination of a run, the depth was slowly increased (the flume was gradually flooded), thus changing the quantity of water in the previously closed system. Therefore, extensive use was made of the bed plotter and manometer board to determine the quantities h and S.

Figure 3-3 is a schematic diagram of the manometer board during a typical run. The water surface is denoted by line 1-1, which has a slope S_s. The line 2-2 represents the water surface after completion of the run (with the flume level). Line 2A-2A represents the surface after correction for the flume slope during the run. Finally, line 3-3 indicates the location of the bed, a distance h' below line 2A-2A. This distance h' was determined by measuring, with a point gauge, the depth of water over a known point, A, on the bed profile (which had previously been levelled off with a trowel). The X-Y plot of the bed profile (such as that shown in Figure 3-4) was used to correct the depth, h', relative to the mean bed elevation. The plot also served to correct the bed slope, S_b, should it differ from the slope of the flume. Thus, the depth during the run was known to be the difference between the manometer readings of line 1-1 (the water surface during the run) and line 3-3 (the bed location during the run).

3-3 Classification of Bed Configuration

As the main objective of this study was to classify the various types of bed configuration, it was necessary to establish a reliable means of identifying each bed form.

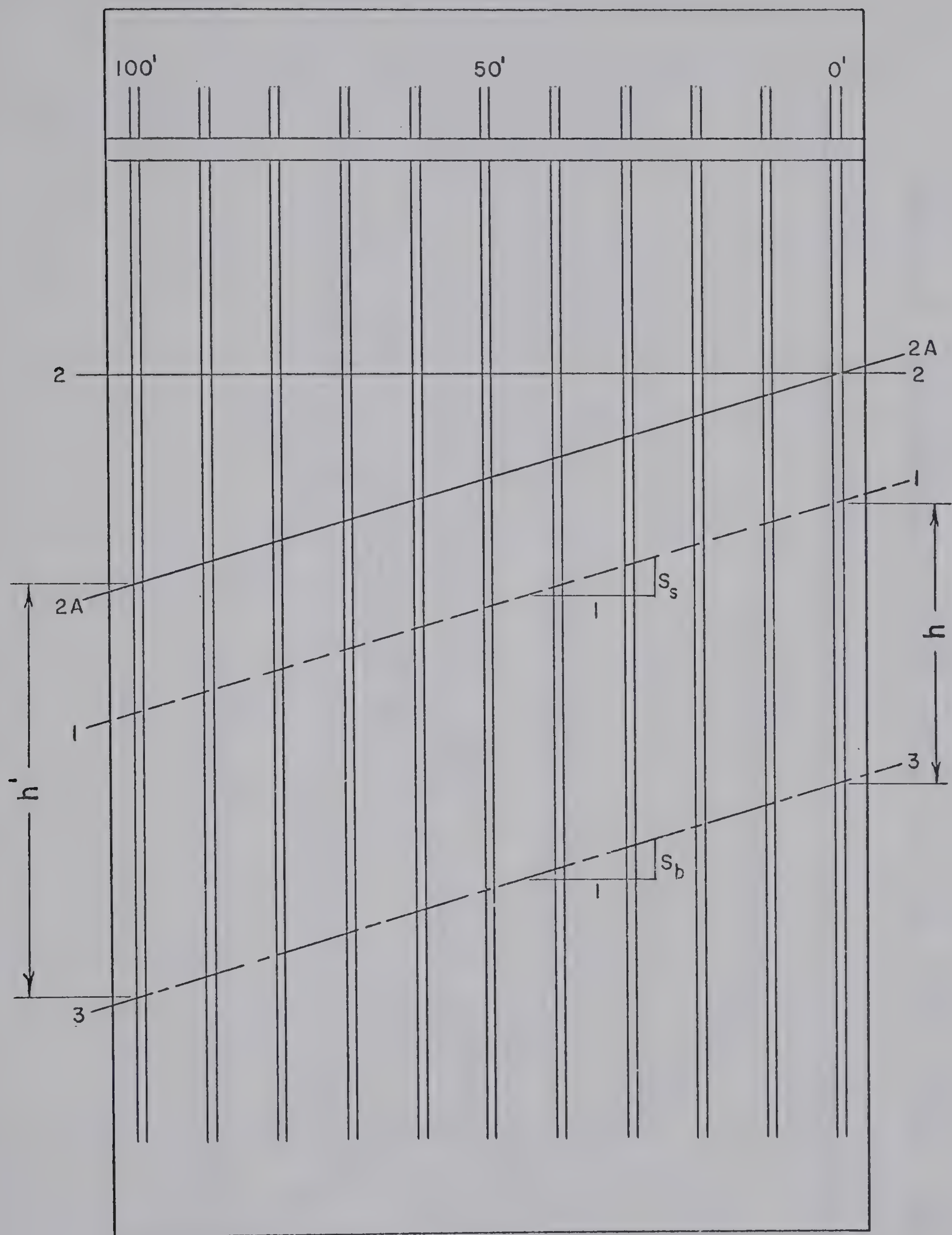


FIG. 3-3. ILLUSTRATION OF USE OF MANOMETER BOARD FOR DETERMINATION OF DEPTH

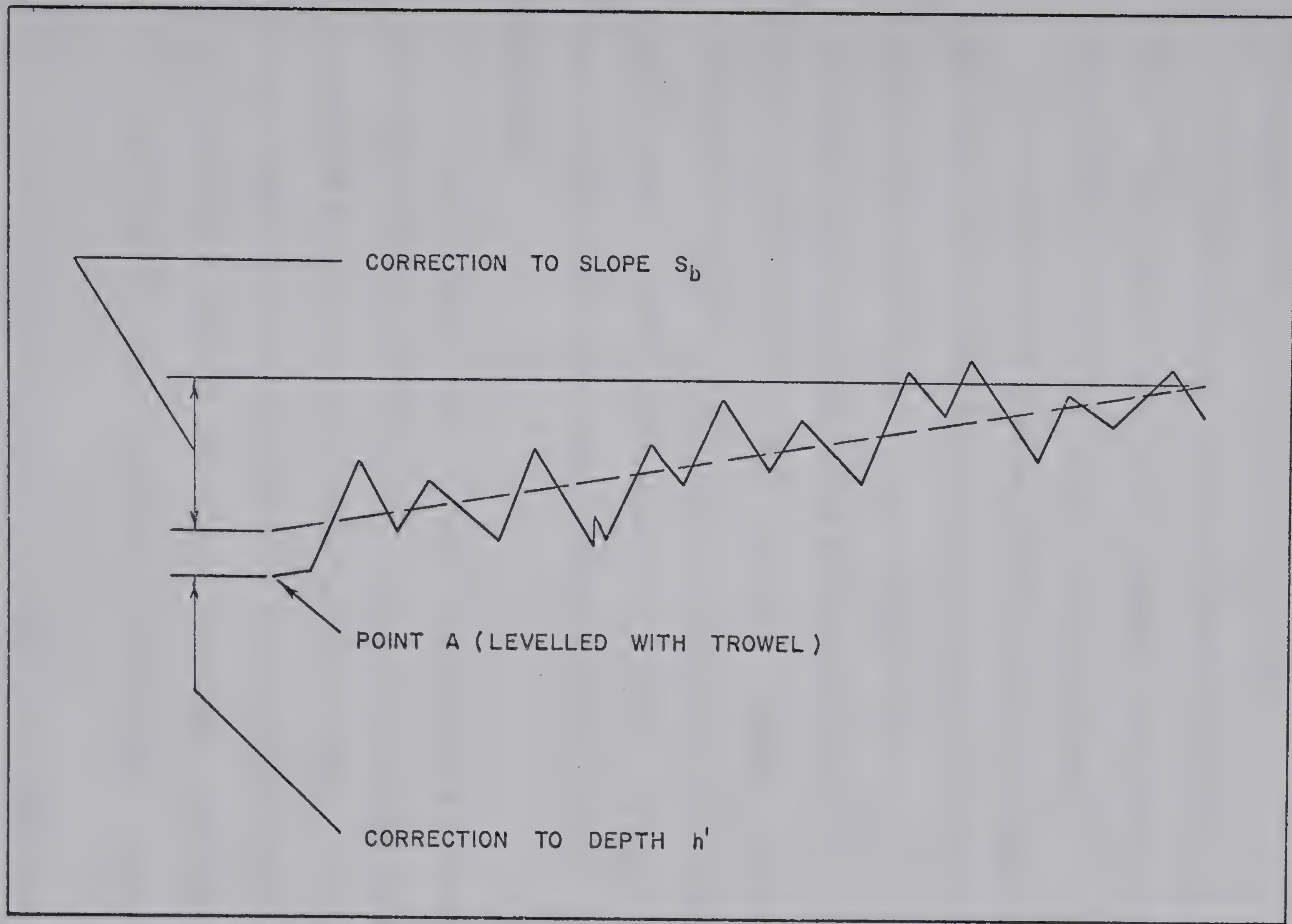


FIG. 3-4. USE OF X-Y PLOT FOR DETERMINATION OF DEPTH

This was primarily accomplished with a visual inspection of the bed, as described more fully, with the aid of photographs, in section 4-2. Unfortunately, the configurations are not as readily identifiable in the photographs as they were in the flume.

The visual identification was largely dependent on Yalin's definitions: "Dunes have a more or less regular two-dimensional shape."[1] and "Ripples have an irregular three-dimensional shape."[2]

As a supplementary means of distinguishing between ripples and dunes, velocity profiles were taken when possible. The intention was to compare log-log plots of these profiles (which appear in the appendix) with those proposed by Simons and Richardson (ref. 11, p. J26) as being typical for particular bed configurations. However, due to the physical limitations of the velocity probe, no measurements were taken in the vicinity of the bed (within approximately 0.03 feet). As such, this supplementary means of bed form identification was not reliable and had to be abandoned.

A supplementary means of identification was also sought to distinguish between dunes and the beginning of the transition to upper regime. It was noted during experimentation that as the flow conditions approached those at transition, the resistance to flow decreased abruptly, resulting in the ponding of water at the foot of the flume, and requiring an adjustment to the depth to restore uniform flow conditions. Conversely, when

1 M.S. Yalin, Geometric Properties of Sand Waves, ASCE Journal of the Hydraulics Division, Volume 90 HY5, September 1964, p. 115.

2 ibid.

the transition was approached from the upper regime side, an abrupt increase in resistance to flow occurred causing a reduced depth at the foot of the flume. The occurrence of these abrupt changes in the resistance to flow were subsequently employed to aid in identification of the bed configuration.

3-4 Procedure

A satisfactory laboratory procedure was developed early in the testing program and was used throughout most of the experimentation. It consisted basically of the following steps:

1. Q and S were set at values which would produce a condition near transition from one bed configuration to another.
2. The flume was filled slowly so as to not disturb the antecedent bed configuration.
3. The run was commenced and h was adjusted to obtain uniform flow over the bed.
4. Depth was readjusted to compensate for any change in the resistance to flow due to bed form development.
5. Uniform flow conditions were maintained for a sufficient length of time to allow complete development of bed forms.
6. Photographs were taken of the flume walls indicating the shape and dimensions of average bed forms.
7. S, Q, C, duration of run (and velocity profiles, if the depth was sufficient) were measured.
8. The run was terminated, the bed profile plotted and the mean depth was determined.
9. The bed was slowly drained (so as to avoid disturbing the

bed forms) and photographs were taken which indicated the shape, size and distribution of bed forms on the bed.

This procedure was followed with various types of antecedent bed configurations (including plane bed).

Runs were also made to determine the possibility of plane bed with slow (rolling) motion. The procedure employed for these tests was basically the same as that previously described. However, the bed was initially brought to a plane condition (hydraulically), then screeded to eliminate any small surface disturbances, such as ripples. The flume was then operated at a condition approaching initiation of motion. As the bed material commenced motion, uniform conditions were maintained and the bed configuration observed over as long a period of time as possible.

Suggestions have been made in the discussion section which require slight changes in the apparatus and consequently in the procedure itself.

CHAPTER IV

EXPERIMENTAL RESULTS

4-1 Presentation of Raw and Compiled Data

Table 4-1 contains the basic observed quantities which were collected during thirty-one runs. In addition to these measurements, other data were collected: (1) velocity profiles; (2) time variation of sediment discharge; (3) time required to reach equilibrium; (4) geometry of bed forms.

The basic data have been reduced to the necessary computed quantities and are contained in Table 4-2.

4-2 Description of Runs

4-2-1 General

The experimentation resulted in bed configurations of four basic categories: (1) ripples near transition to dunes; (2) dunes near transition from ripples; (3) dunes near transition to plane bed; (4) plane bed near transition from dunes. No runs were made to determine the phase boundaries within upper regime.

4-2-2 Ripples

A total of nine runs were made which resulted in a ripple bed. This configuration was developed from both plane bed (screeded by hand) and dune bed conditions. The ranges covered by the most important quantities were: Froude number (0.016 to 0.032), slope (0.00075 to 0.00115), h/D (232 to 399) and C (0.2 ppht to 5.3 ppht). Visual identification

TABLE 4.1 BASIC OBSERVED QUANTITIES

RUN	Q	h	S	C	BED FORM	DURATION OF RUN	WATER TEMPERATURE	WAVE LENGTH	WAVE HEIGHT
	cfs	ft.	%	ppht		hrs.	°F	ft.	in.
1	0.50	0.176	0.137	3.3	Dunes*	24	90	0.44	0.5
2	0.63	0.095	0.360	48.3	Dunes	12	83	0.52	0.6
3	0.37	0.113	0.200	3.2	Dunes	20	83	0.51	0.55
4	0.93	0.334	0.080	1.2	Ripples	8	85	0.48	0.6
5	0.48	0.210	0.080	0.5	Ripples	11	83	0.44	0.45
6	0.48	0.205	0.110	0.6	Dunes	10	85	0.45	0.45
7	0.33	0.192	0.090	1.1	Dunes	12	81	0.43	0.45
8	0.33	0.198	0.075	0.3	Ripples	12	82	0.44	0.4
9	0.33	0.199	0.075	0.2	Ripples*	48	87	0.44	0.45
10	0.40	0.213	0.090	0.2	Ripples	23	83	0.46	0.45
11	0.40	0.180	0.105	0.5	Dunes	48	83	0.45	0.45
12	0.60	0.231	0.090	0.5	Dunes	23	83	0.45	0.5
13	0.61	0.246	0.080	1.6	Ripples	20	82	0.43	0.55
14	0.75	0.281	0.080	2.8	Ripples	20	83	0.55	0.45
15	0.75	0.280	0.115	5.3	Ripples	22	82	0.46	0.5
16	0.75	0.279	0.090	1.3	Dunes	17	86	0.44	0.5
17	0.50	0.202	0.095	3.7	Dunes	23	84	0.42	0.4
18	0.60	0.173	0.380	83.5	Dunes	6	82	0.55	0.5
19	0.60	0.106	0.700	625.0	Plane	6	82	-	-
20	0.62	0.060	0.660	226.0	Plane	5	84	-	-
21	0.62	0.155	0.380	118.4	Dunes	10	84	0.55	0.6
22	0.50	0.172	0.480	50.1	Dunes	5	79	0.52	0.45
23	0.50	0.113	0.705	598.8	Plane	3	78	-	-
24	0.45	0.054	0.640	55.5	Dunes	5	78	0.41	0.4
25	0.45	0.071	0.530	185.0	Dunes	7	78	0.42	0.3
26	0.40	0.106	0.570	212.7	Dunes	4	78	0.42	0.3
27	0.40	0.044	0.680	286.6	Plane	9	79	-	-
28	0.50	0.132	0.750	1063.0	Plane	6	78	-	-
29	2.00	0.340	0.075	-	Ripples	10	80	0.44	0.55
30	1.90	0.318	0.085	-	Dunes	9	83	0.50	0.65
31	2.00	0.250	0.300	-	Dunes	8	83	0.90	0.80

* ANTECEDENT CONDITION WAS PLANE BED (SCREEDED BY HAND)

\- NOT MEASURED OR NOT APPLICABLE

TABLE 4.2 QUANTITIES COMPUTED FROM EXPERIMENTAL DATA

RUN	FR'	h/D	$\tau_o V$ (lbs/ft-sec) X 10^{-2}
1	0.054	206.3	0.982
2	0.545	111.4	3.378
3	0.112	132.5	1.093
4	0.027	391.6	0.995
5	0.029	246.2	0.542
6	0.032	240.3	0.747
7	0.018	225.1	0.423
8	0.016	232.1	0.351
9	0.016	233.3	0.351
10	0.019	249.7	0.508
11	0.032	211.0	0.601
12	0.034	270.8	0.755
13	0.030	288.4	0.678
14	0.030	329.4	0.821
15	0.030	328.2	1.180
16	0.030	327.1	0.924
17	0.036	236.8	0.673
18	0.082	202.8	3.274
19	0.356	124.3	6.222
20	2.096	70.3	6.198
21	0.121	181.7	3.411
22	0.058	201.6	3.448
23	0.204	132.5	5.205
24	1.515	63.3	4.375
25	0.666	83.2	3.593
26	0.158	124.3	3.378
27	2.212	51.6	4.152
28	0.128	154.7	5.488
29	0.119	398.6	2.000
30	0.132	372.8	2.174
31	0.302	293.1	8.320

was the primary means of classifying the bed forms as being ripples. As such, numerous photographs were taken during and after each run so as to obtain a visual record of the bed configuration. The ripple configuration consisted of forms, usually smaller than dunes, which did not span the flume breadth (transversely). This is illustrated by Plates 4-1 to 4-4.

4-2-3 Dunes

Seventeen of the runs made resulted in a duned bed. This configuration was developed from both ripple and upper regime (plane) antecedent conditions. The ranges encountered in the basic quantities were: Froude number (0.018 to 0.515), slope (0.00085 to 0.0064), h/D (63 to 373) and C (0.5 ppht to 213 ppht).

The dune configuration was visually unique in that the forms were generally larger than ripples and tended to extend across the entire width of the flume. This feature is evident in Plates 4-5 to 4-10.

Although the longitudinal shape of the dune and ripple forms were quite similar, the dunes near transition to upper regime seemed to be somewhat more elongated (this becomes evident in a comparison of the ripple beds of Plates 4-11 to 4-14 with the dune beds of Plates 4-15 to 4-18).

4-2-4 Plane Bed

Five runs were completed in the plane bed configuration. The antecedent conditions included duned and plane beds. The basic quantities varied over the following ranges: Froude number (0.128 to 2.212), slope (0.0066 to 0.0075), h/D (52 to 155) and C (226 ppht to 1063 ppht).

The plane bed was easily distinguished, visually, as is evident in Plates 4-19 to 4-21. In some instances, however, it was discovered

PLATE 4 - I. RIPPLE BED OF RUN IO

PLATE 4 - 2. RIPPLE BED OF RUN IO

PLATE 4 - 3. RIPPLE BED OF RUN 14

PLATE 4 - 4. RIPPLE BED OF RUN 15

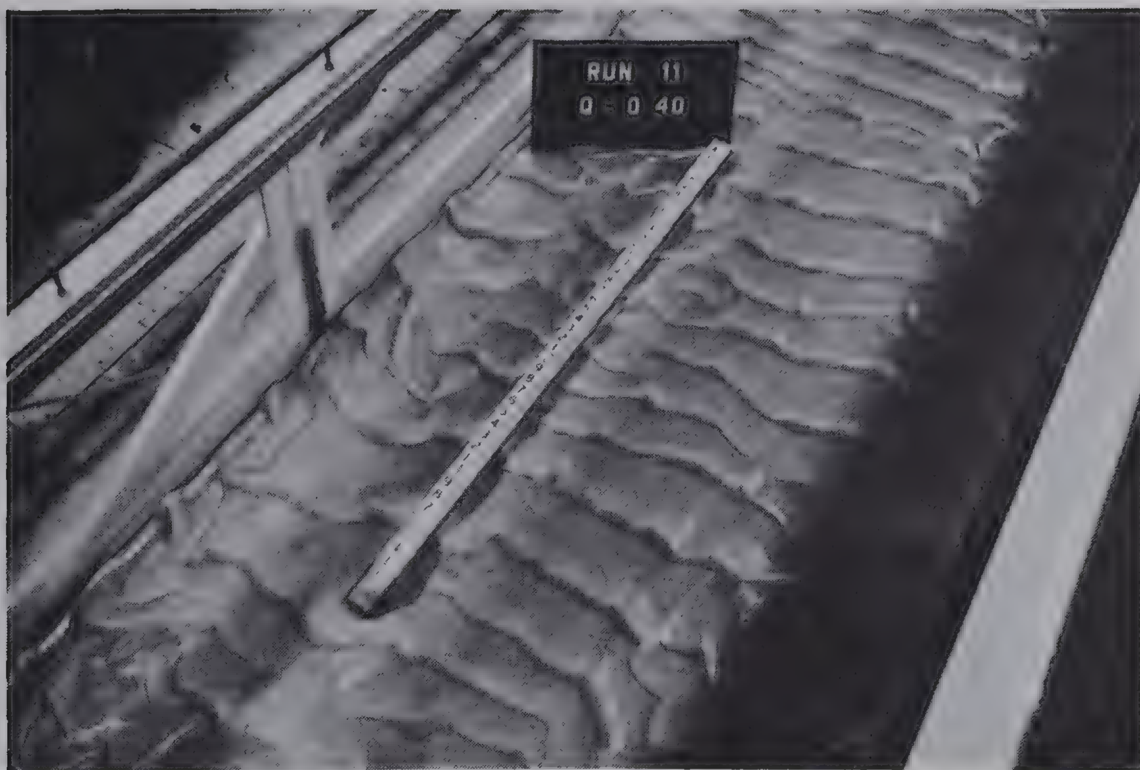


PLATE 4 - 5. DUNE BED OF RUN 11

PLATE 4 - 6. DUNE BED OF RUN 16

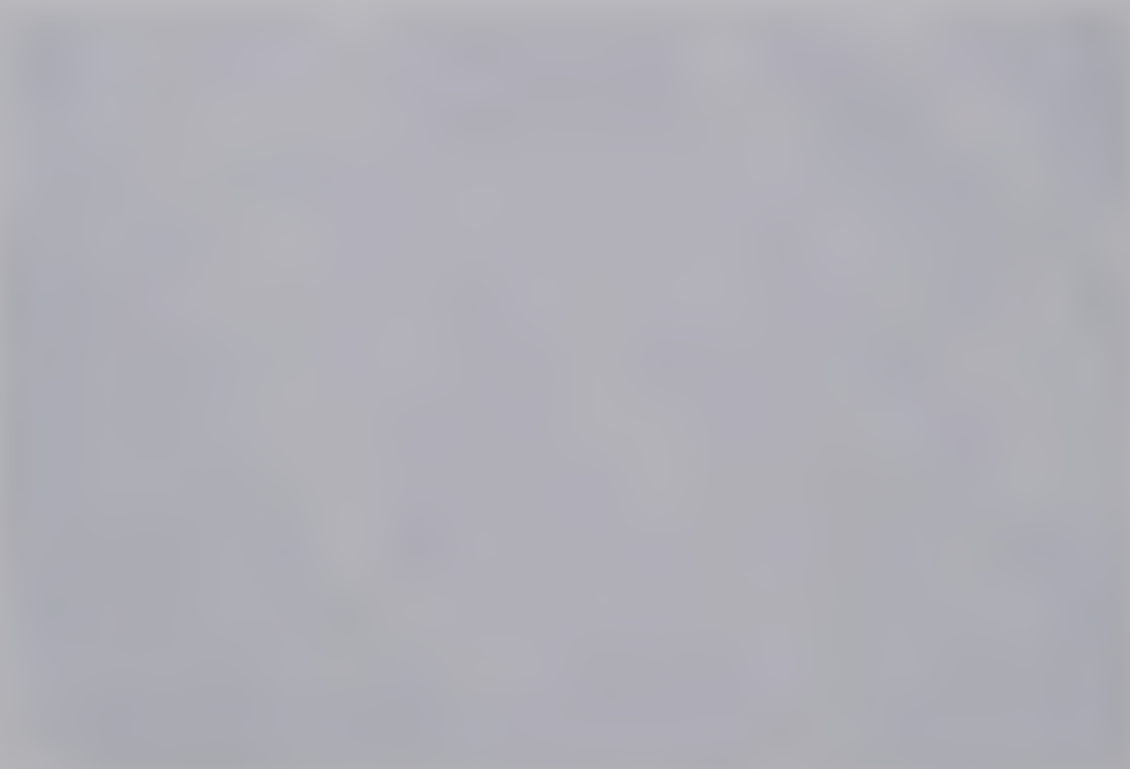
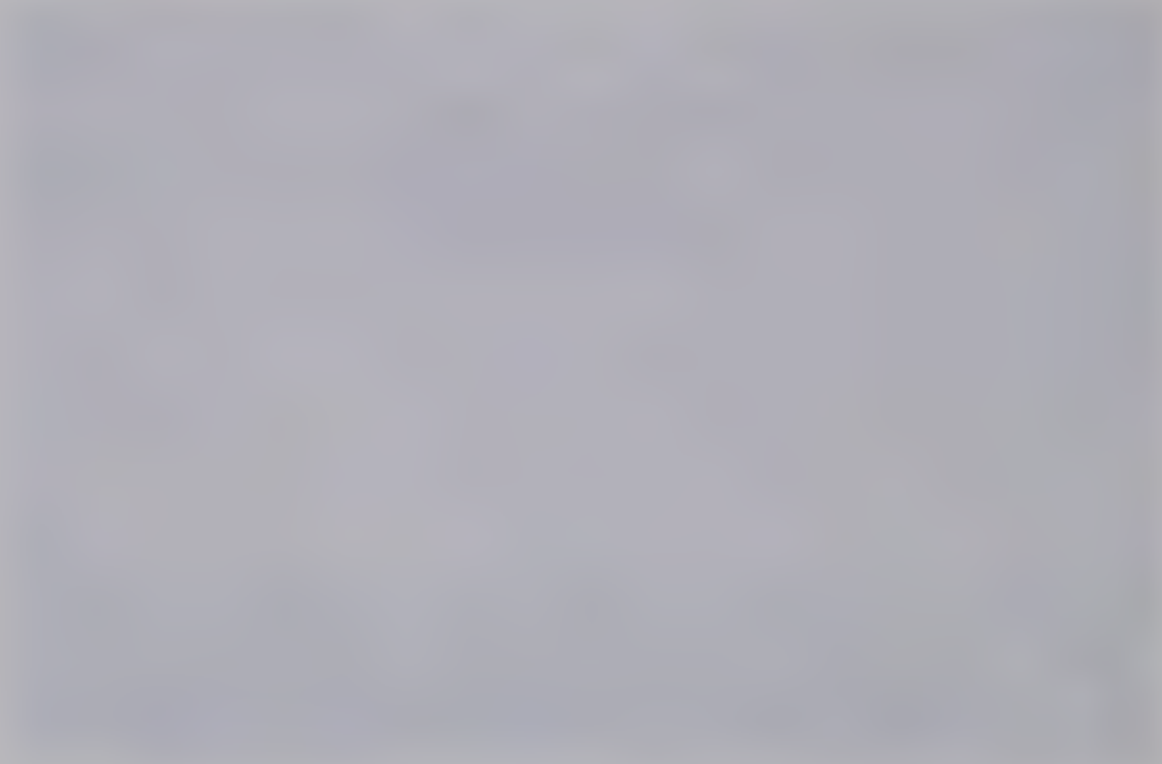


PLATE 4 - 7. DUNE CONFIGURATION OF RUN 17

PLATE 4 - 8. DUNE BED OF RUN 22

PLATE 4 - 9. DUNE CONFIGURATION OF RUN 22

PLATE 4 - 10. DUNE BED OF RUN 24



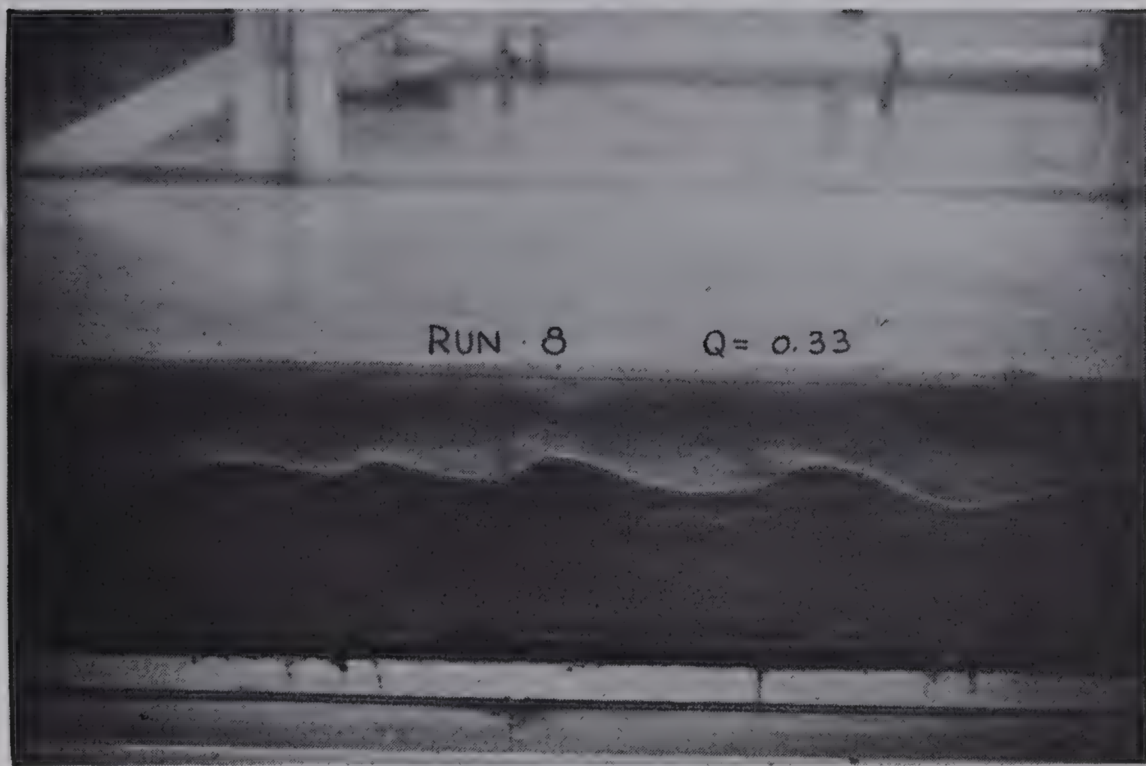


PLATE 4-11. RIPPLE FORMS OF RUN 8

PLATE 4-12. RIPPLE FORMS OF RUN 13

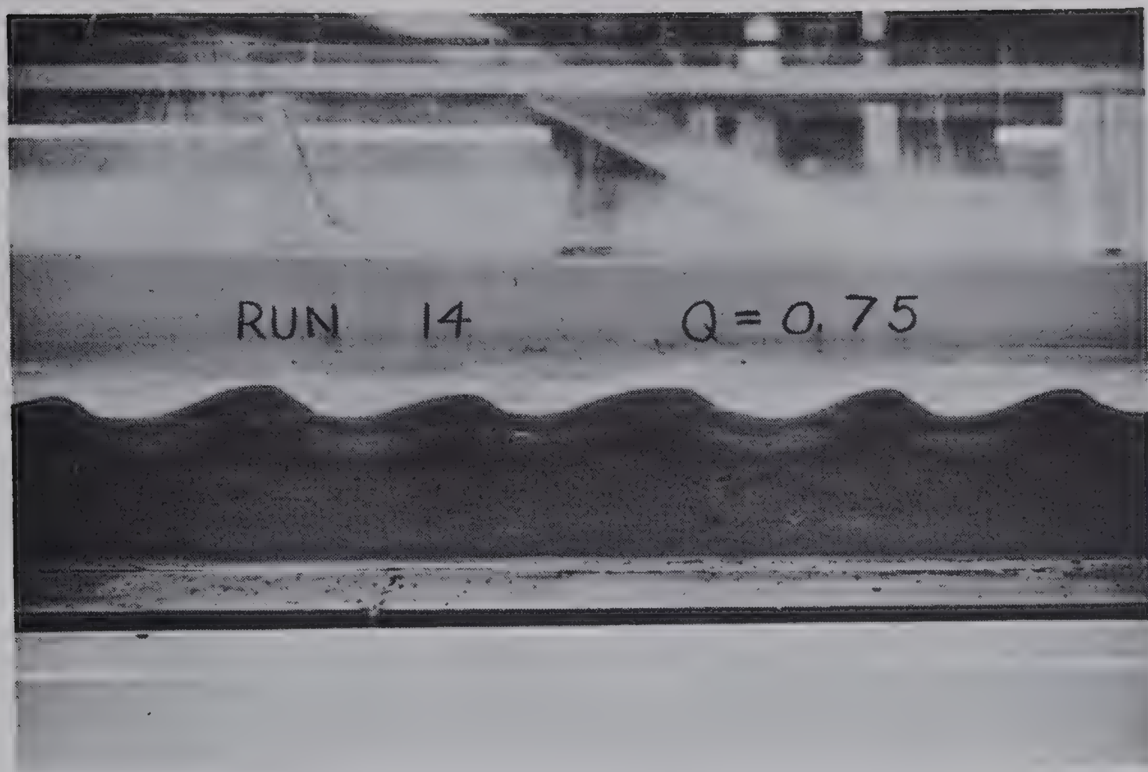


PLATE 4 - 13. RIPPLE FORMS OF RUN 14

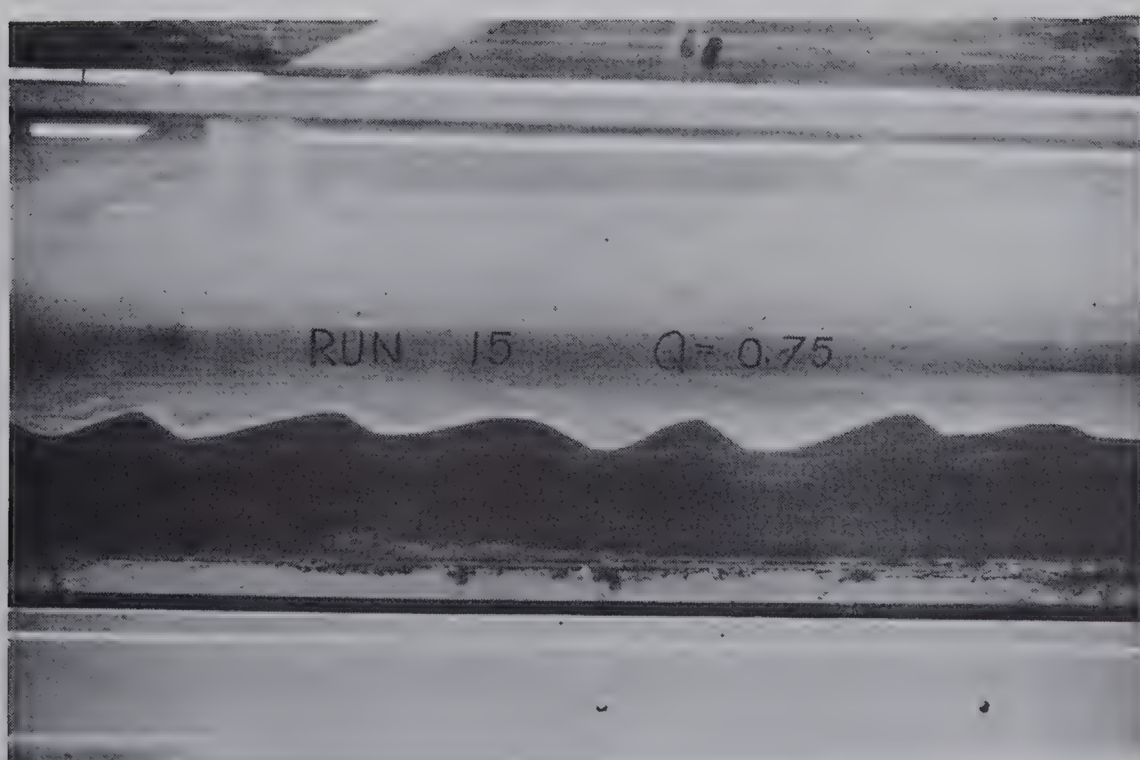
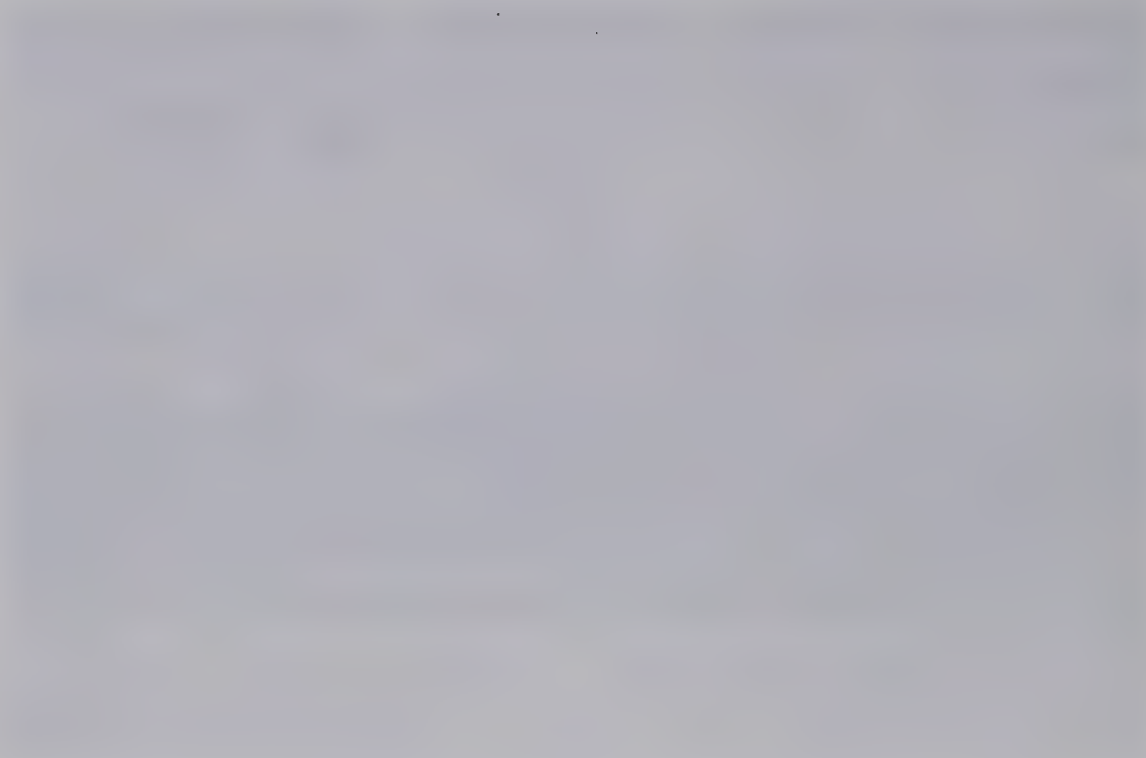
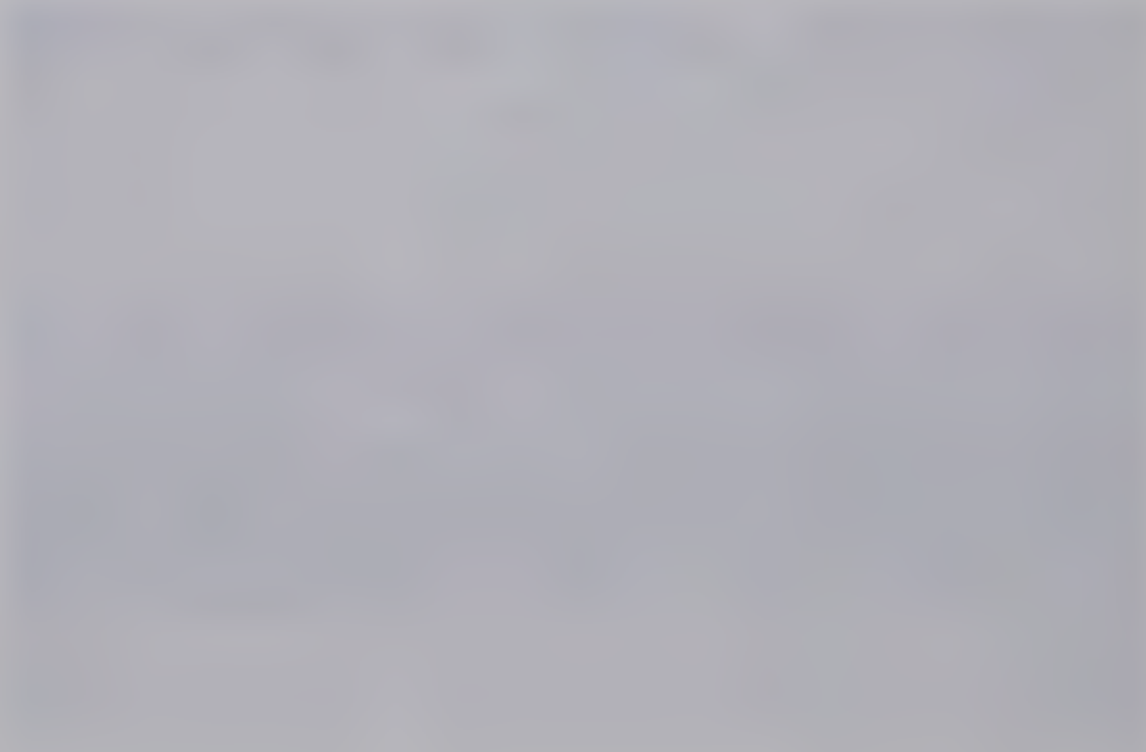


PLATE 4 - 14. RIPPLE FORMS OF RUN 15





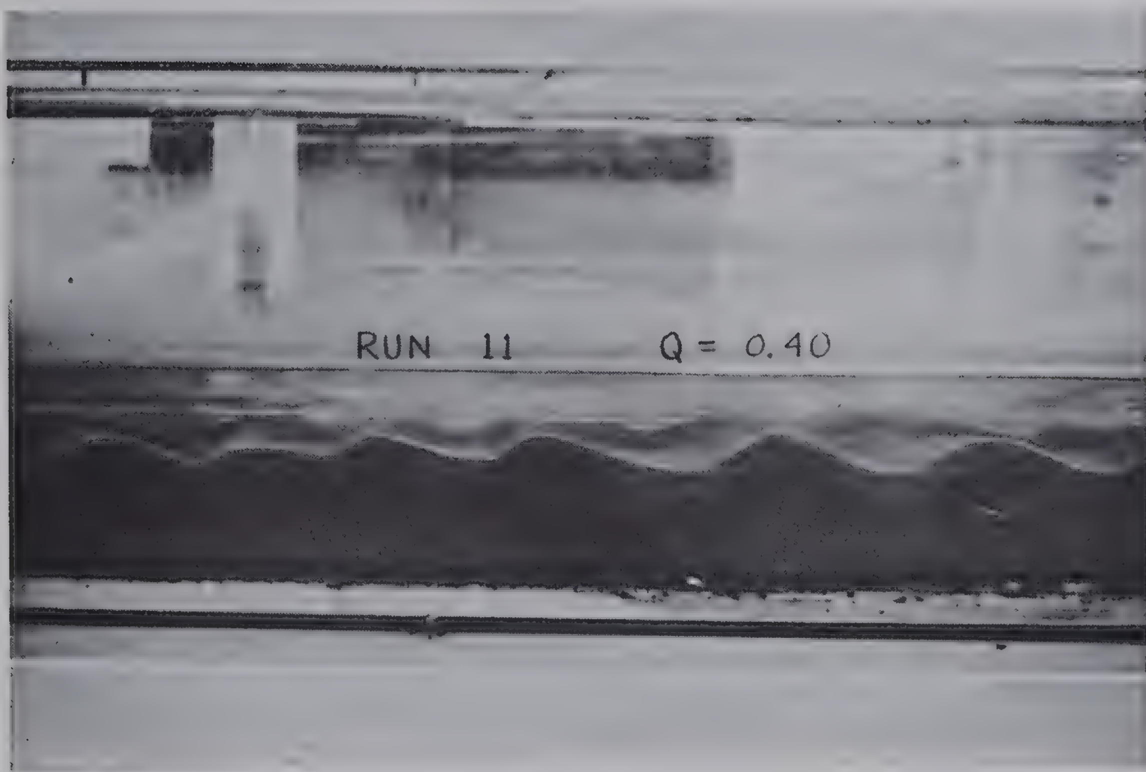


PLATE 4-15. FORM OF DUNES NEAR TRANSITION FROM RIPPLES (RUN 11)

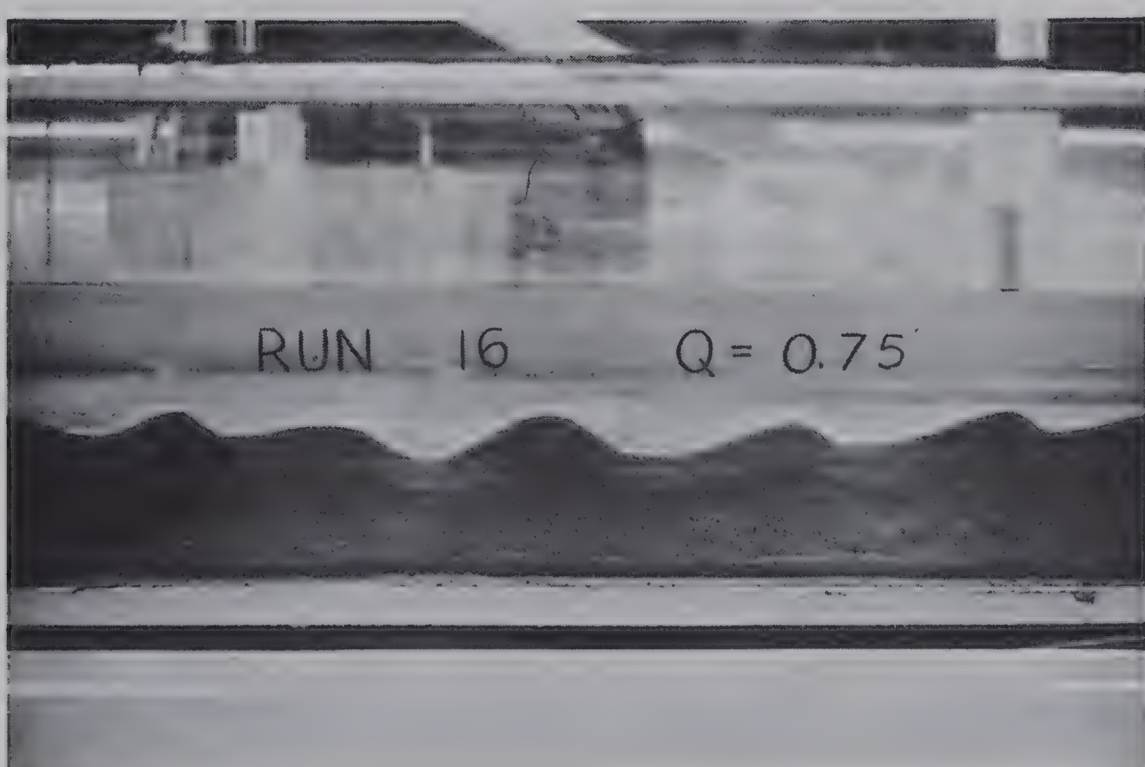


PLATE 4-16. FORM OF DUNES NEAR TRANSITION FROM RIPPLES (RUN 16)

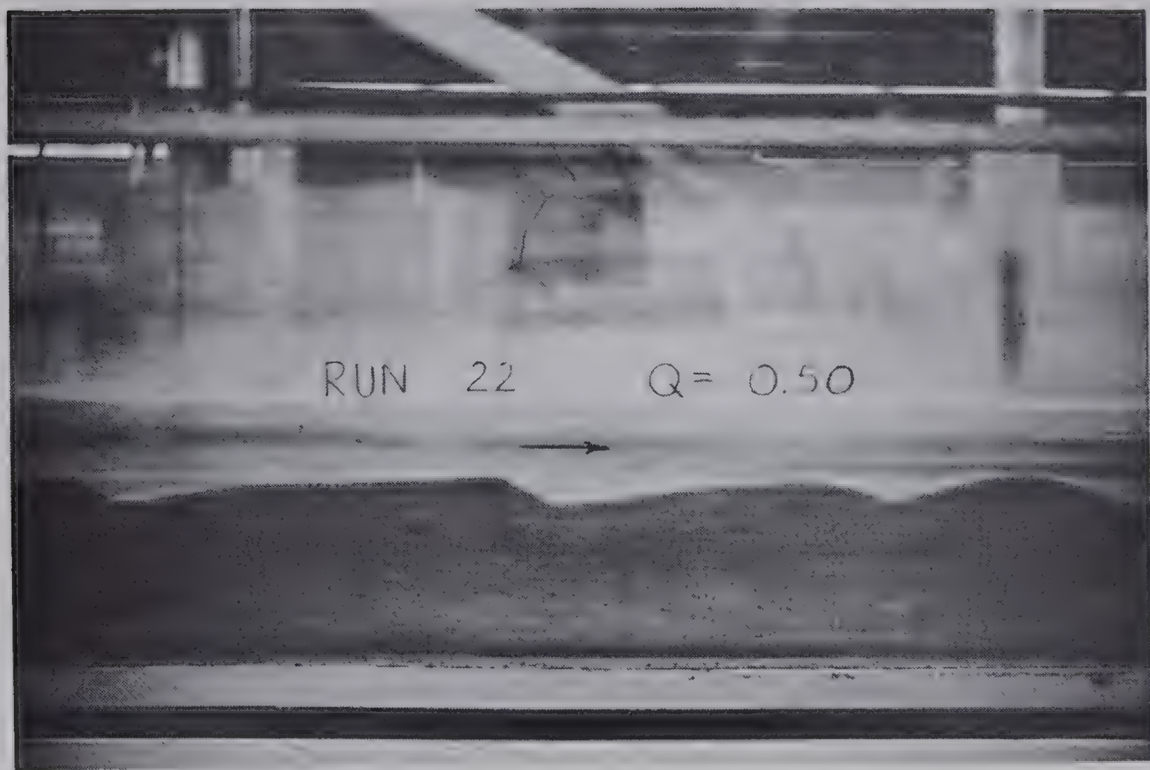


PLATE 4-17. FORM OF DUNES NEAR TRANSITION TO PLANE BED (RUN 22)

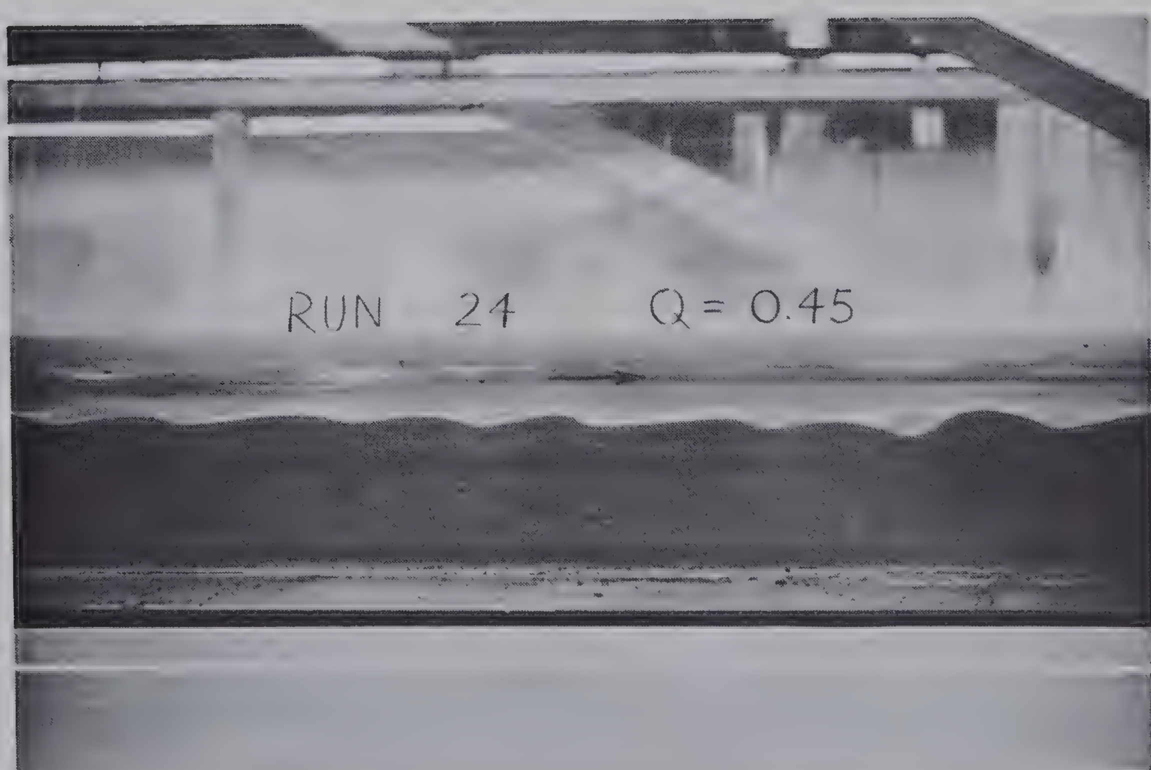


PLATE 4-18. FORM OF DUNES NEAR TRANSITION TO PLANE BED (RUN 24)

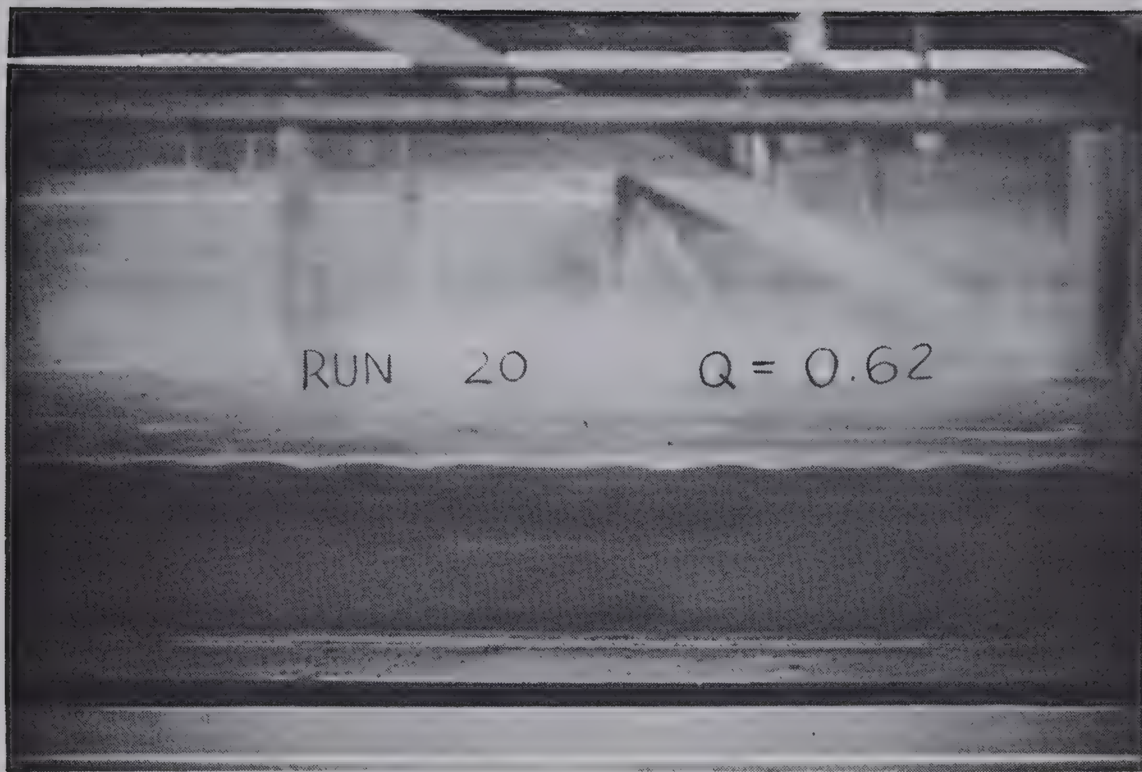


PLATE 4 - 19. PLANE BED OF RUN 20

PLATE 4 - 20. PLANE CONFIGURATION OF RUN 19

PLATE 4 - 21. PLANE BED OF RUN 19

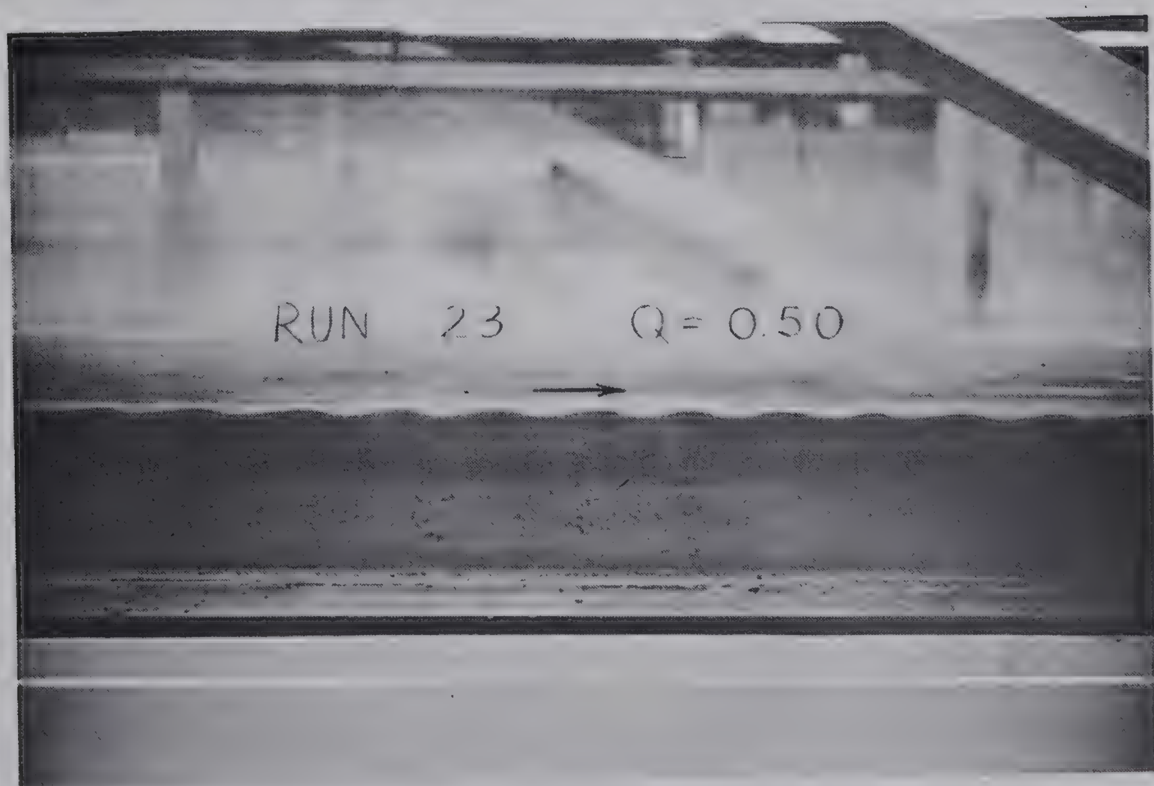


PLATE 4 - 22. SMALL DUNE FORMS NEAR WALL (RUN 23)

upon completion of the run that some patches of very low, flat dunes existed near the flume walls (see Plates 4-22 to 4-24). This was generally encountered when any tendency towards meandering within the flume walls occurred.

4-2-5 Plane Bed at Low Charge

Although several runs were made in an attempt to obtain plane bed with rolling motion (at low charge) this configuration could not be maintained. In all the runs the bed, which had initially been screeded to a plane condition, developed a ripple formation. An example of this phenomenon is shown in Plate 4-25.

4-3 Supplementary Data

During the course of experimentation certain data were collected which were of interest but not of direct importance to this study. A plot of the time variation of sediment discharge (as determined by periodic sampling) is included in the appendix as Figure A-1. Profiles of the bed at various elapsed times after commencement of a run (to determine the time required to reach equilibrium) are illustrated by Figures A-2 to A-4 respectively, in the appendix. Finally, Figures A-5 to A-16 represent the previously discussed velocity profiles, and Figures A-17 to A-27 are the bed profiles which were plotted at the termination of each run.

4-4 Presentation of Results

The basic quantities, as derived in Chapter V, are graphically illustrated by the two-dimensional plots of Figures 4-1 to 4-7. In addition to the experimental points, the transitional boundaries as proposed by Cooper (3) are also plotted.

PLATE 4 - 23. SHALLOW DUNE FORMS NEAR WALL (RUN 27)

PLATE 4 - 24. SHALLOW DUNE FORMS NEAR WALL (RUN 28)

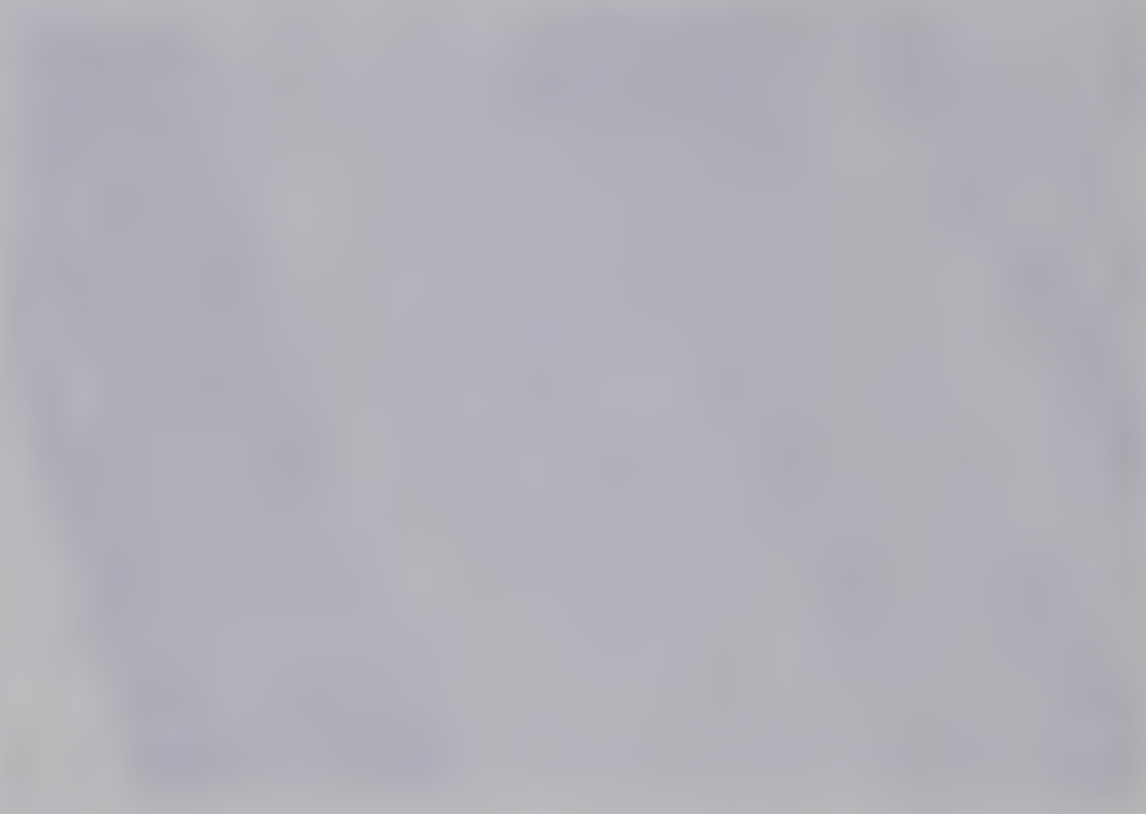
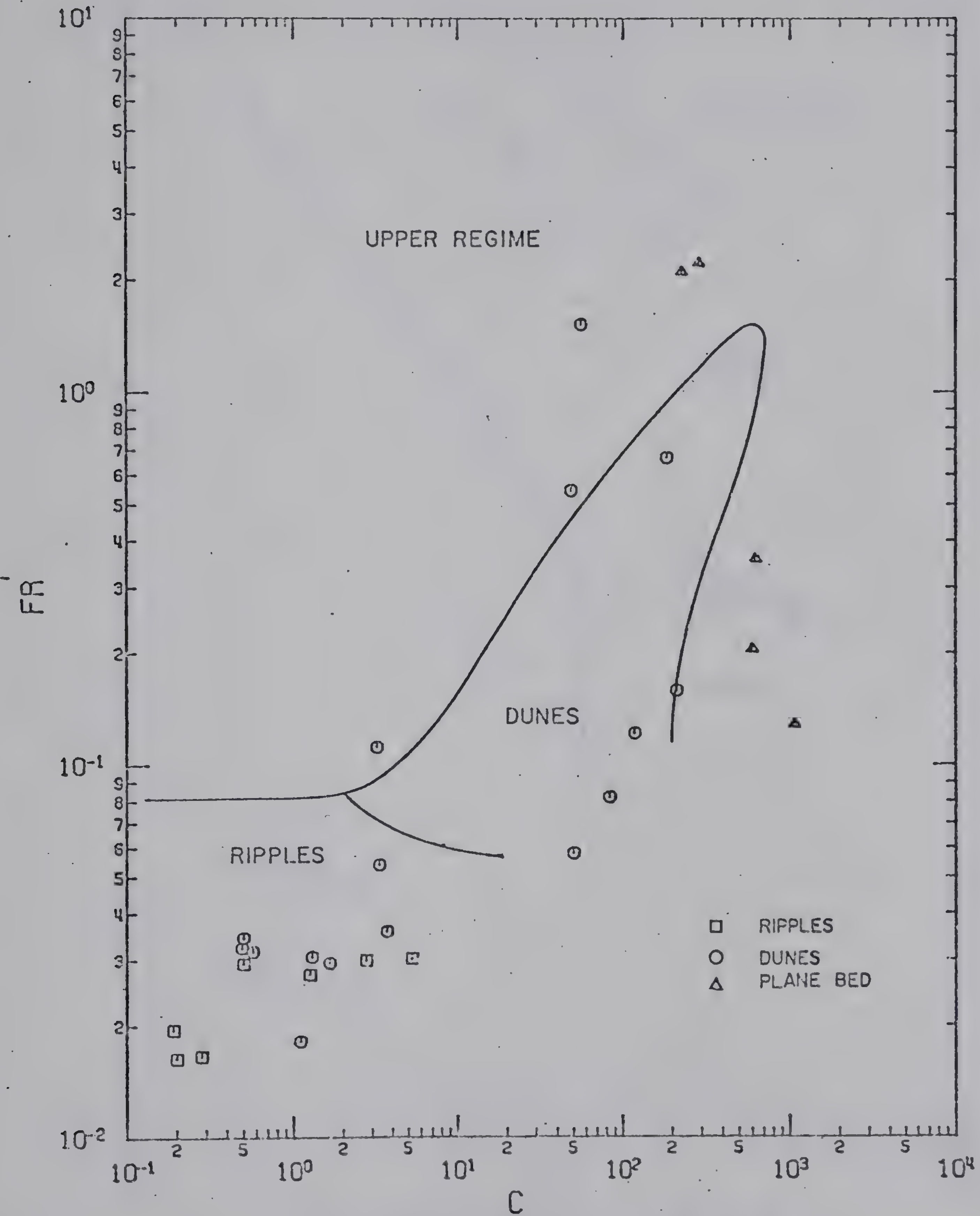
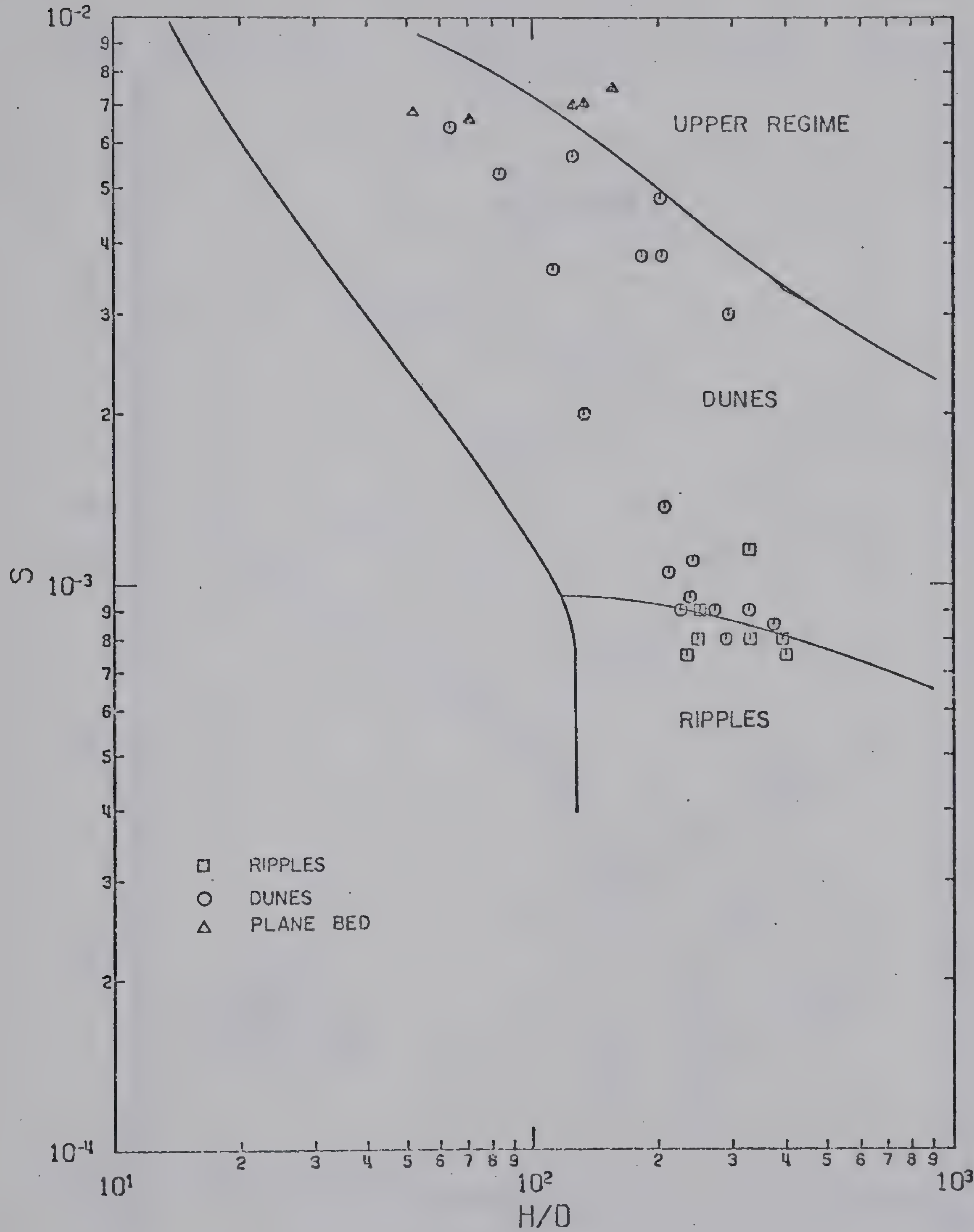


PLATE 4-25. DEVELOPMENT OF RIPPLES ON PLANE BED AT LOW CHARGE



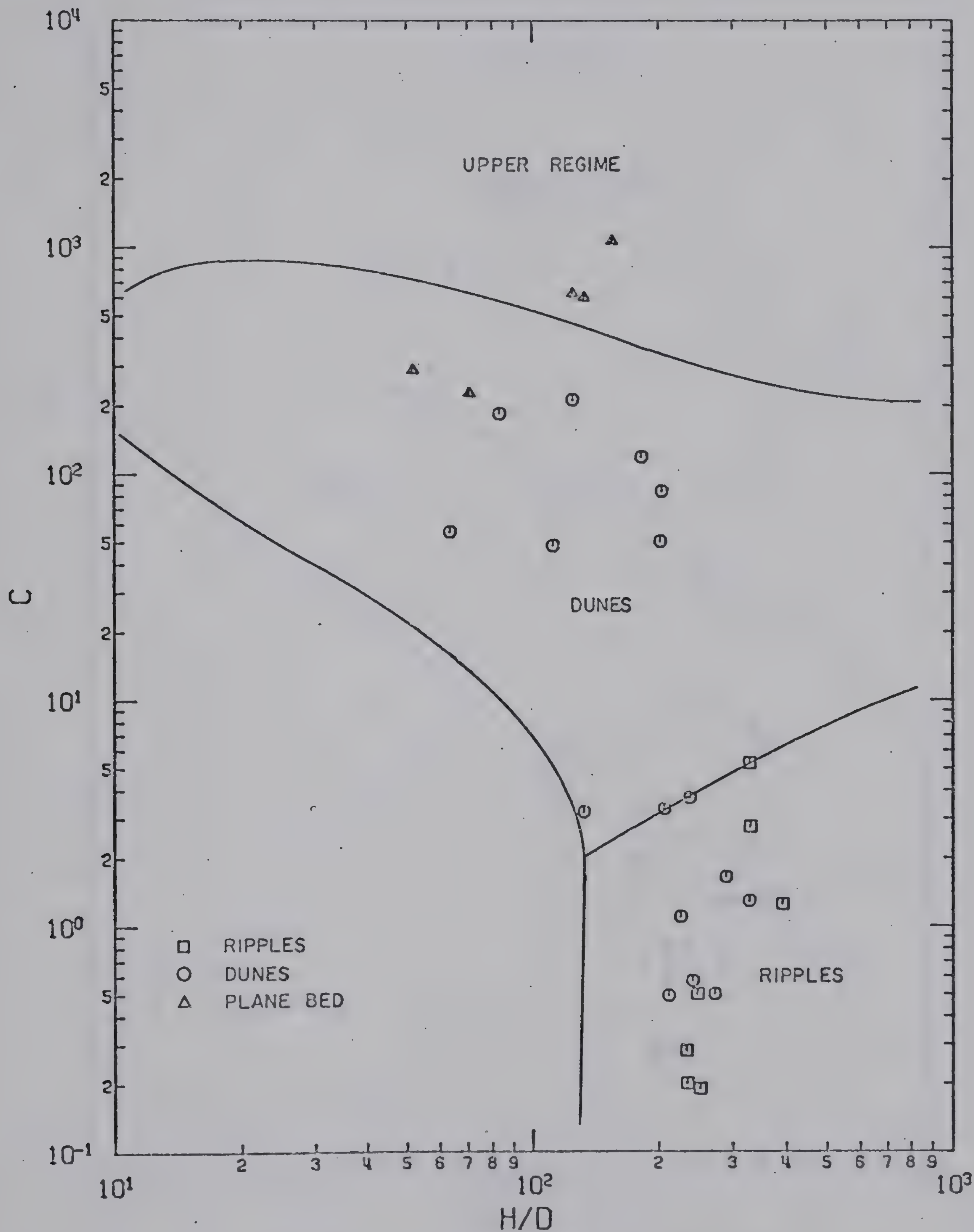
BED CONFIGURATION - FR' VS C

FIGURE 4-1



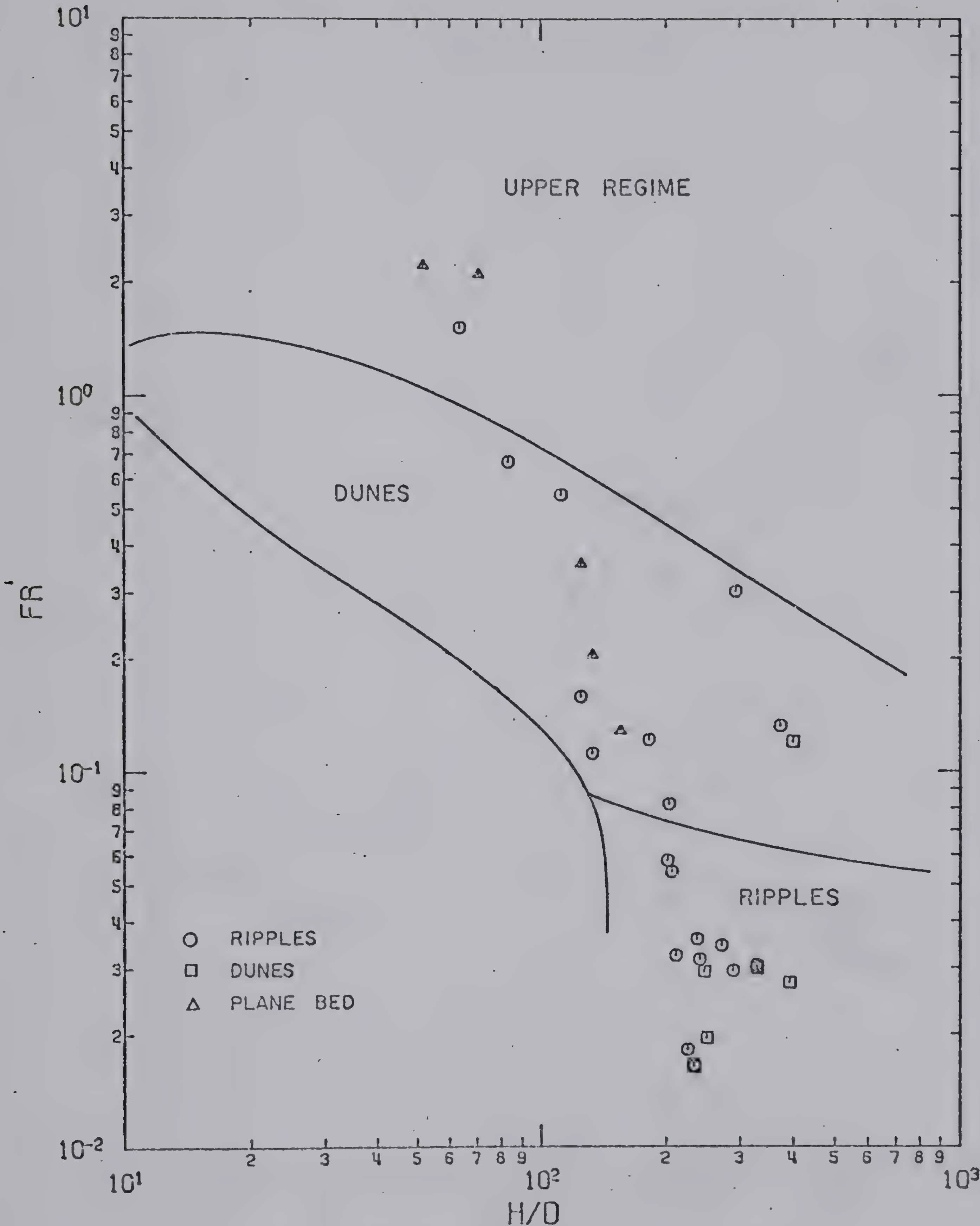
BED CONFIGURATION - S VS H/D

FIGURE 4-2



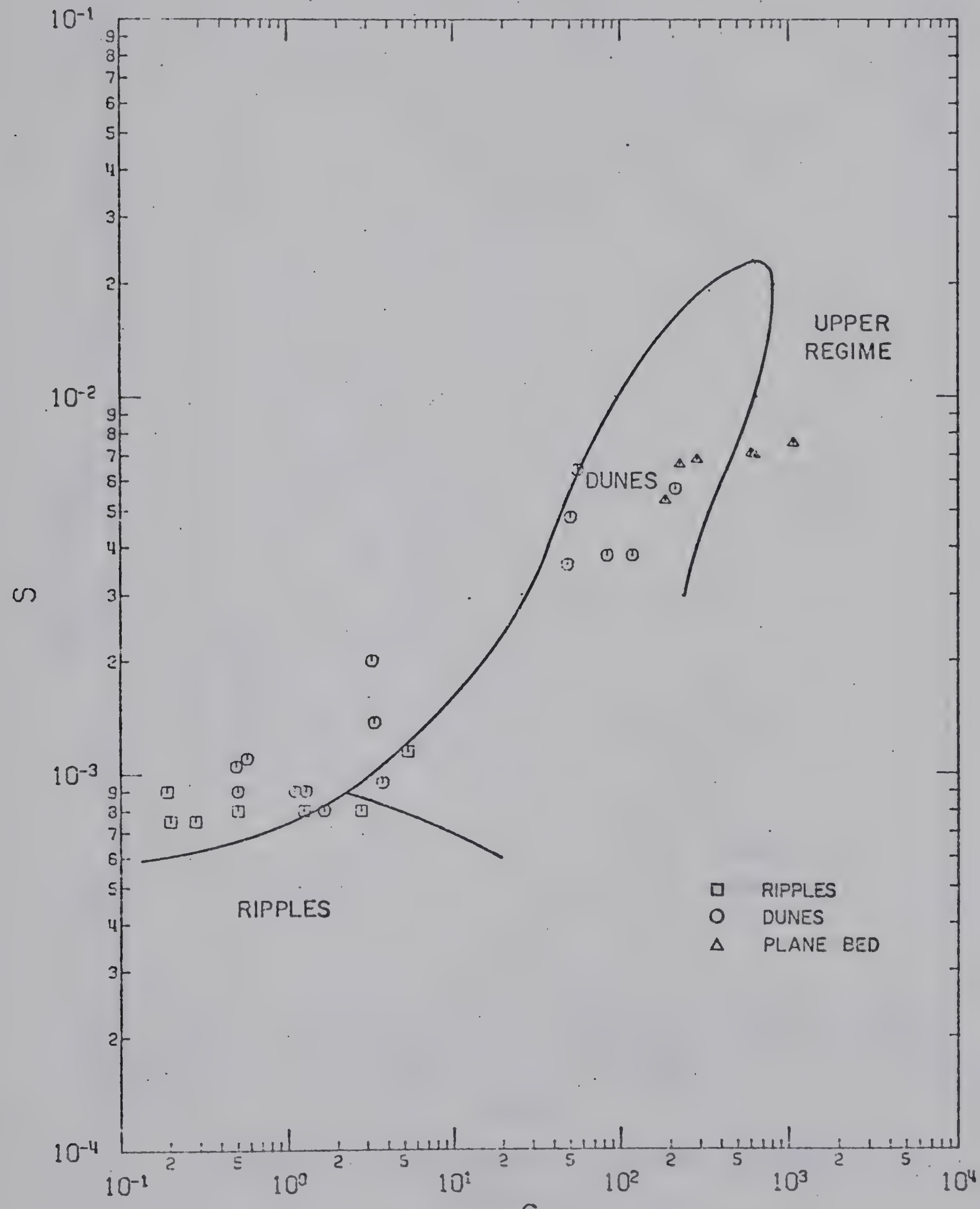
BED CONFIGURATION - C VS H/D

FIGURE 4-3.



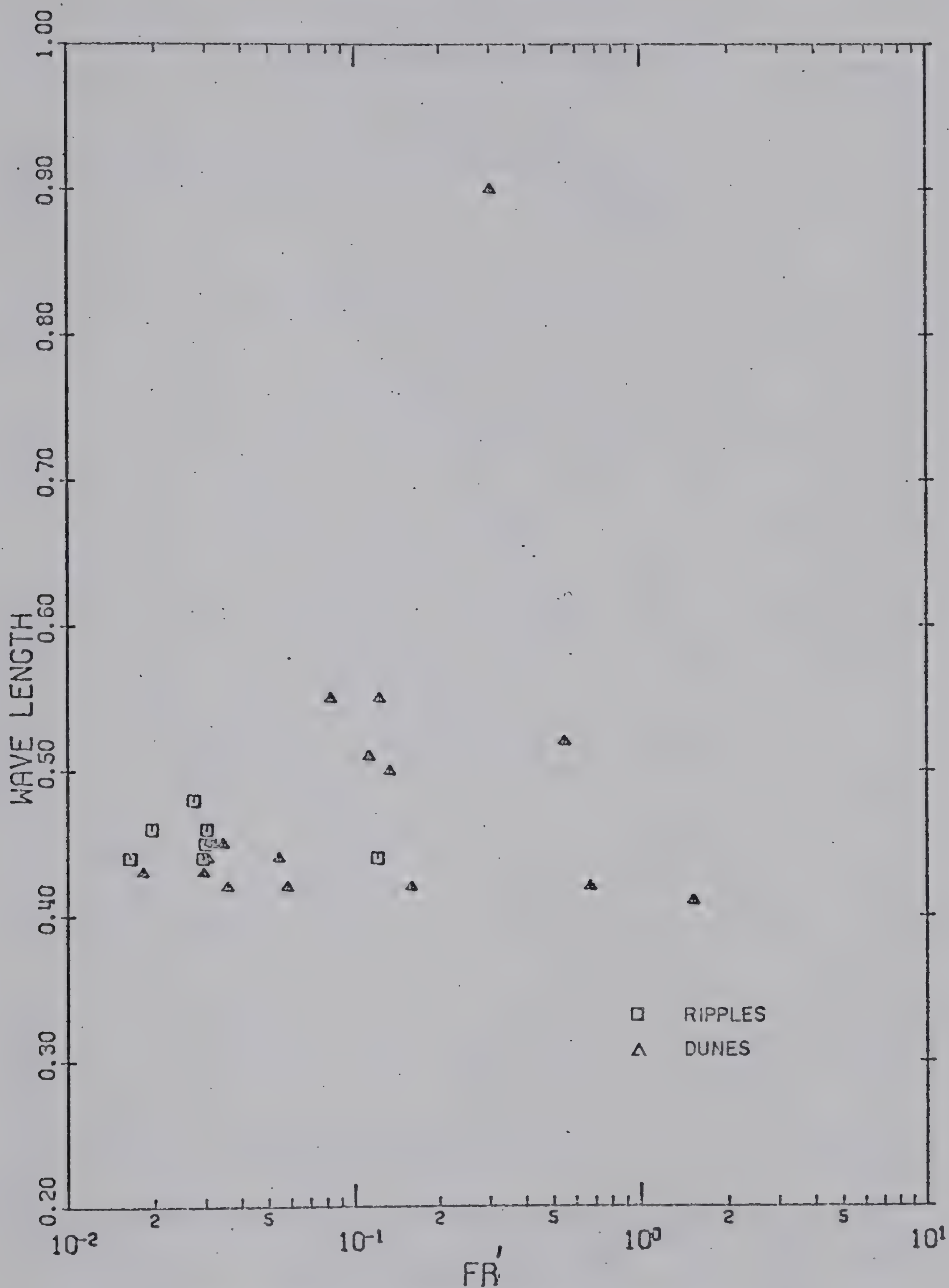
BED CONFIGURATION - FR' VS H/D

FIGURE 4-4.



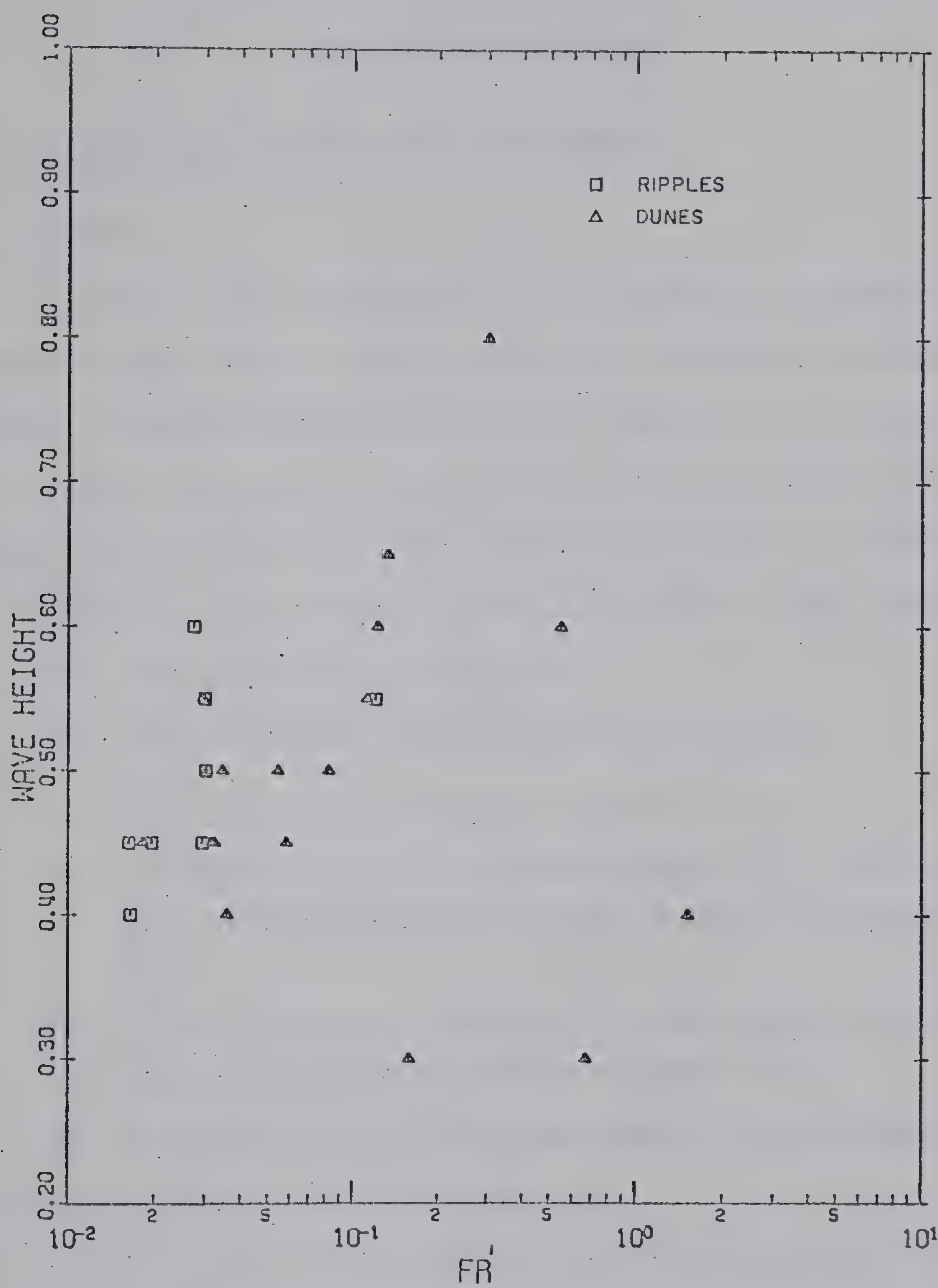
BED CONFIGURATION - S VS C

FIGURE 4-5.



BED CONFIGURATION - LAMBDA VS FR'

FIGURE 4-6.



BED CONFIGURATION - DELTA VS FR'

FIGURE 4-7.

CHAPTER V

ANALYSIS AND DISCUSSION

5-1 Prediction of Bed Forms and Their Behavior

5-1-1 General

As stated in the introduction, it is desirable to establish a mathematical model which, when provided with a minimum of independent variables, would predict bed configuration. However, before such a model can be constructed, all the variables which are related to the phenomenon must be specified. Thus, the following physical properties must be present in the statement of the problem (for a flume study):

(1) flume properities (breadth, b).

(2) fluid properties (density ρ_f, and viscosity, ν).

(3) coefficient of gravitational acceleration, g.

(4) bed material properties (median diameter, D_{50}, density, ρ_b, and a factor to account for particle shape, gradation, etc., X).

(5) the flow properties (discharge, Q, mean velocity, V, slope, S, depth, h, and rate of sediment transport, C).

(6) bed form properties (type, wavelength, λ, wave height, Δ).

Therefore, the general problem statement is:

$$V,\ S,\ C,\ \lambda,\ \Delta \ = \ fn\ (Q,\ h,\ \rho_f,\ \nu,\ b,\ \rho_b,\ D_{50},\ X,\ g) \qquad (5\text{-}1)$$

Thus, a dimensionally complete statement must contain ten variables. According to dimensional analysis theory (ref. 2), the presence of three

basics (mass, length, and time) fixes the number of dimensionless parameters at seven. If the starting variables chosen are:

$$\text{fn} \quad (\rho_b, \rho_f, X, b, h, \nu, D_{50}, g, V, C) = 0 \tag{5-2}$$

then one possible set of parameters is:

$$\text{fn} \quad (FR', \frac{h}{D_{50}}, C, V_i, \frac{\rho_b}{\rho_f}, X, \frac{b}{h}) = 0 \tag{5-3}$$

Where $FR' = \dfrac{\rho_f V^2}{g(\rho_b - \rho_f)h}$ and $V_i = 3 \dfrac{\sqrt{\nu g}\, D_{50}}{\nu}$

The last four parameters in the list are assumed to be either constant or ineffectual (although V_i would vary with any change in bed material, it remained constant during this study). Thus, a simple, practical statement which describes the mathematical model is:

$$\text{fn} \quad (FR', \frac{h}{D_{50}}, C) = 0 \tag{5-4}$$

Similarly, if the starting variables are:

$$\text{fn} \quad (\rho_b, \rho_f, X, b, h, \nu, D, g, S, C) = 0 \tag{5-5}$$

then a second statement which defines the system is:

$$\text{fn} \quad (S, C, h/D) = 0 \tag{5-6}$$

Thus, the mathematical model may be represented graphically with a three-dimensional co-ordinate system upon which the bed configuration boundaries may be indicated.

5-1-2 Comparison of Prediction Schemes

In order to verify the mathematical model thus obtained, it would be useful to be able to compare it with other models derived from previous

analyses. Unfortunately, the most widely accepted prediction scheme (that of Simons and Richardson, as shown in Chapter II) employs a unique measured quantity, fall diameter, and is not dimensionless. Similarly, Liu's model (see Chapter II), although dimensionless, employs the variable ω, fall velocity, which inhibits direct comparison of solution curves. As such, only the Simons and Richardson criterion is useful as a basis for comparison with the experimental results.

Figure 5-1 illustrates the experimental data, as well as curves which best fit the Gilbert data, in relation to the Simons and Richardson curves. By inspection, it becomes obvious that the data and curves are in agreement only with respect to the sequence of bed form development. Admittedly, the Gilbert data contain no points which are classified as ripples; however, it appears as though the transitions in bed configuration occur at significantly lower values of stream power ($\tau_o V$) than those predicted by Simons and Richardson.

In order to gain a better understanding of the Simons and Richardson criterion for prediction of bed configuration, it becomes necessary to examine its derivation from a dimensional analysis point of view. The original problem statement in the derivation (1964) is:

$$\text{Form} = \text{fn}\ (S, D, h, \omega, \rho, \Delta) \tag{5-7}$$

The last two variables may be eliminated from the expression by specifying a range of experimental conditions. Thus, the expression becomes:

$$\text{Form} = \text{fn}\ (S, D, h, \omega) \tag{5-8}$$

Simons and Richardson state that "The variables were not grouped into dimensionless parameters for discussion purposes to avoid masking the

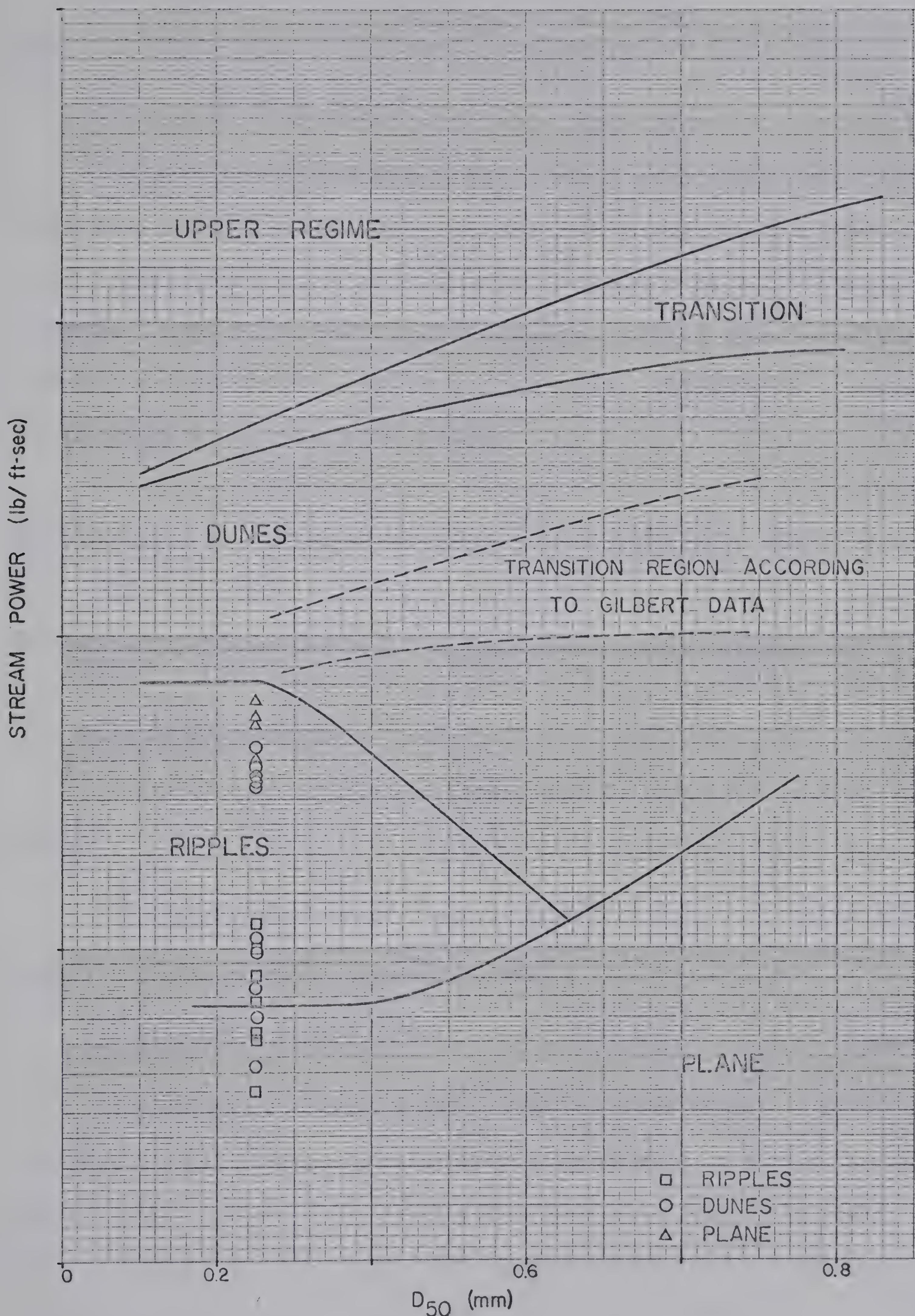


FIG. 5-1. SIMONS AND RICHARDSON CRITERION FOR PREDICTION OF BED FORM

essential role of any one of them.",[1] and derived the final solution:

$$\text{Form} = \text{fn}\ (\tau_o V,\ D_{fall}). \tag{5-9}$$

The Simons and Richardson solution would contain the proper number of parameters, if the quantities involved were dimensionless. However, by lumping several quantities together with V to form a physically meaningful parameter, $\tau_o V$, the authors appear to have eliminated these quantities from further consideration in the problem. This is analagous to attempting to reduce a statement of the form:

$$X = \text{fn}\ (Y,\ Z,\ W) \tag{5-10}$$

(which results in a solution surface in three dimensions, to the form:

$$XYZ = \text{fn}\ (W) \tag{5-11}$$

(which may be represented by a two-dimensional co-ordinate system).

5-2 Bed Form Dimensions

If the list of starting variables from Section 5-1-1 were as follows:

$$\text{fn}\ (\rho_b,\ \rho_f,\ X,\ b,\ h,\ \nu,\ D_{50},\ g,\ V,\ \lambda) = 0 \tag{5-12}$$

another set of parameters may be derived:

$$\text{fn}\ (FR',\ h/D,\ \lambda/D) = 0 \tag{5-13}$$

Although the analysis of wave length and wave height is beyond the scope of this study, a special effort was made to collect data which might be useful for such an investigation at a later date. As such, the average height and length of the waves for each run were plotted

1 Simons, D.B., Richardson, E.V., and Nordin, C.F.JR., "Sedimentary Structures Generated by Flow in Alluvial Channels", The Society of Economic Paleontologists and Mineralogists, The American Association of Petroleum Geologists, Special Publication No. 12, p. 47.

against FR' as shown in Figures 4-6 and 4-7.

As the bed form geometry data were considered to be unreliable, no direct comparisons could be made with the work of other authors. It is significant, however, that Yalin (13) considered only the parameters h/D and λ/D in his plot which predicts bed form configuration (see Figure 5-2).

5-3 Discussion

Due to the nature of this experimental study, a number of problems were encountered. Basically, the difficulties arose from the large number of variables involved in the phenomenon of sediment transport. It was one thing to assume that a transition in bed configuration might occur near a point with certain flow conditions, and yet another thing to attempt to stabilize the experimental system at that point. Although only two quantities could be imposed on the system (eg. Q and h), the time required for the remaining variables to reach their equilibrium values changed from run to run.

This fact led to some problems related to the actual operation of the flume. The system was allowed more than adequate time (up to forty-eight hours) in which to reach equilibrium. This resulted in a substantial amount of evaporation which affected the depth of flow (by reducing the volume of water in the closed system). Thus, one of the supposedly "imposed" quantities was actually slowly changing throughout the run.

The amount of time required to complete a run was also affected by rapid adjustments in Q, S or h. An increase in discharge or a decrease in slope or depth caused the downstream end of the bed to momentarily assume control over the flow. This invariably caused scour for some

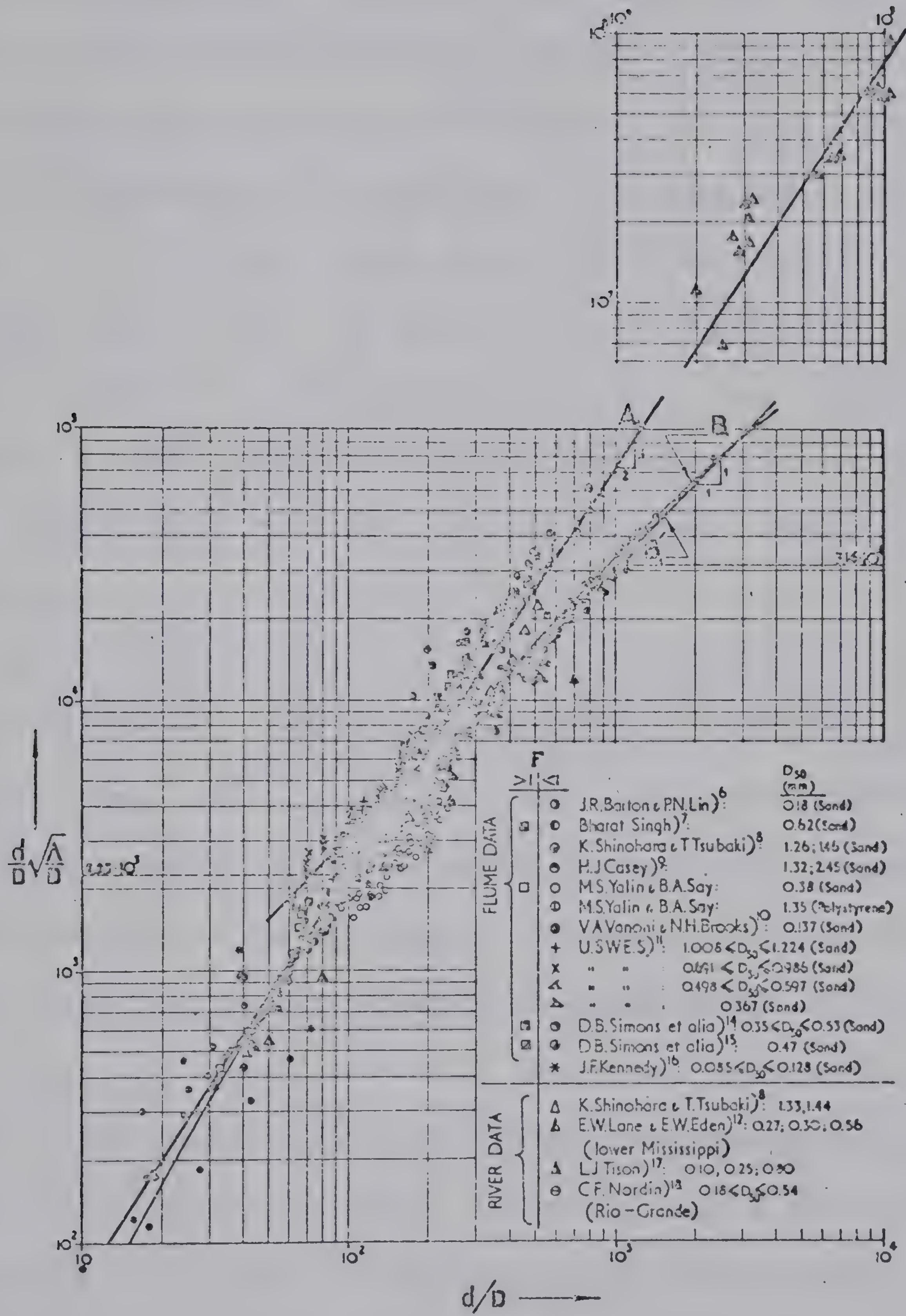


FIG. 5-2. YALIN CRITERION FOR PREDICTING BED CONFIGURATION

distance upstream and eventually resulted in deposition of the removed material at the upstream end of the flume. Thus, more time was required to reach the desired flow conditions, and to restore the bed to its original condition (approximately parallel to the flume bed).

This characteristic instability of the sand bed in the vicinity of the inlet to the pump (at the foot of the flume) also affected the total load samples. The time variation of total sediment discharge, as shown in Figure A-1 in the appendix, resulted in large deviations from the mean. As these surges could not be controlled, it was decided to accept them as being inevitable and take as large a number of samples as possible.

As mentioned in Section 5-2, the bed form geometry data obtained were unsatisfactory. This resulted from the bed plotter's lack of sensitivity which often led it to smooth out the extremities of bed forms and even caused it to skip over some of the smaller forms. Furthermore, it was impossible to use the plotter during the run (which would have greatly simplified the determination of depth) as the relatively large head on the probe caused scouring of the bed and resulted in a false profile. This inability to obtain reliable information about bed form geometry was especially critical. Due to the size of bed material employed and to the range of h/D encountered, the dimensions of ripples and dunes were of the same order of magnitude (which hampered bed form identification).

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6-1 Summary and Conclusions

The object of this study has been to define, as precisely as possible, the conditions at which transition in bed configuration occur. A review of existing knowledge indicated that many theories are limited by their analytical approach and that others have not considered all of the variables relevant to the sediment transport phenomenon. As such, an attempt has been made to develop a mathematical model and establish its validity by comparison with experimentally derived points.

The mathematical model was developed by means of dimensional analysis so as to ensure the completeness of the final result and to eliminate as many simplifying assumptions as possible. Its final form may be expressed as:

$$fn \ (FR', C, h/D) = 0 \tag{6-1}$$

and

$$fn \ (S, C, h/D) = 0 \tag{6-2}$$

The model, upon which the phase boundaries proposed by Cooper (3) were plotted, was evaluated by placing the experimental points on two-dimensional plots of the parameters stated in Equation 6-1. The boundaries, which were derived from a voluminous amount of flume data, were, for the most part, substantiated by the experimental data from this study.

However, it is felt that the Cooper curves at the transition from dunes to upper regime should, in fact, be a zone. One significant result of this change would be that two distinct families of C contours would exist (on the Fr' versus h/D plot, say) in the transition zone. Figure

6-1 shows some hypothetical contours of C superimposed on the Fr' versus h/D plane. In the transition region, C is expected to be greater if the antecedent condition in the bed form development were plane bed rather than dunes.

Furthermore, it would seem from the experimental points that the transition from ripples to dunes occurs at lower values of FR' than those proposed by Cooper. This boundary could perhaps be adjusted as indicated by Figure 6-1.

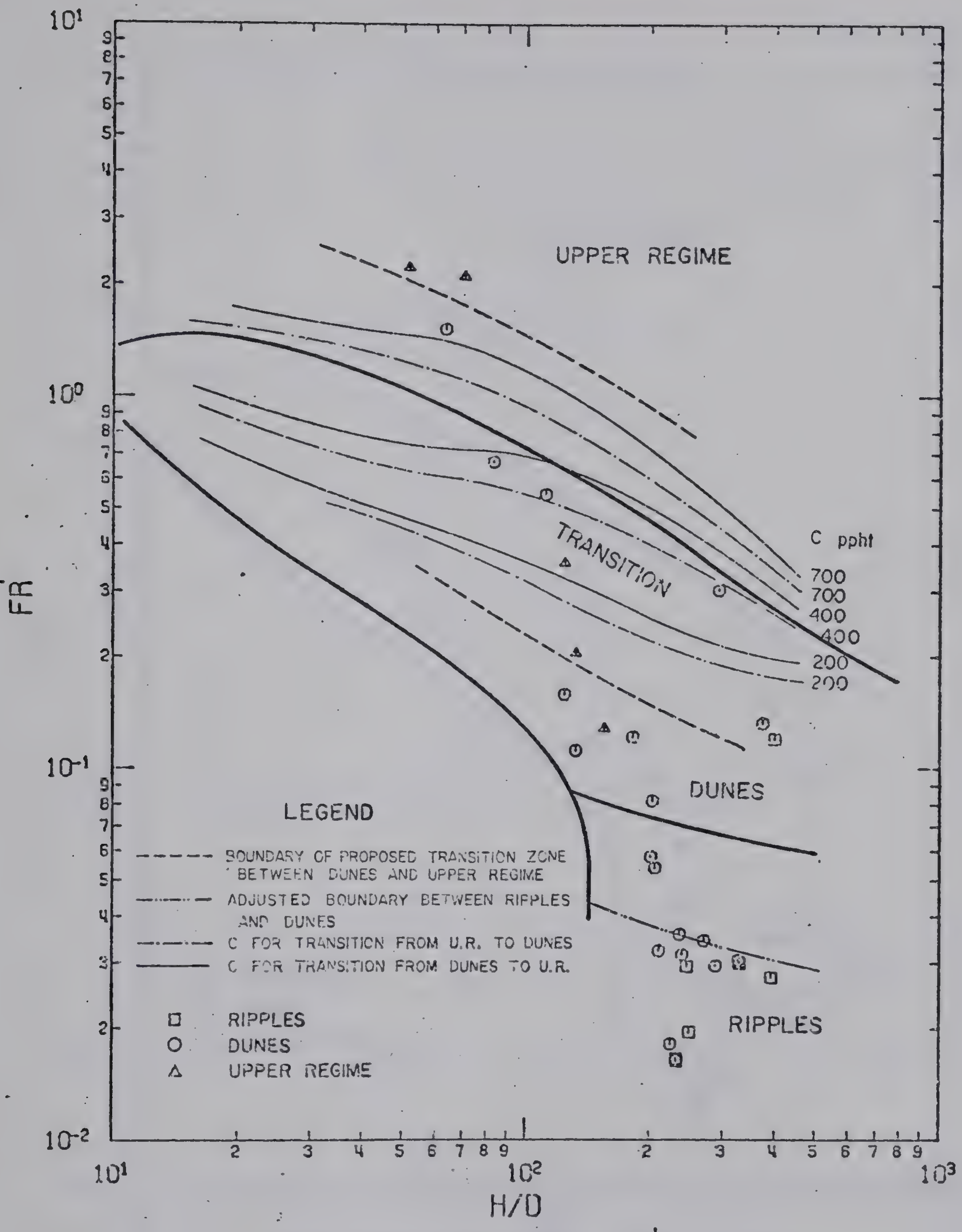
The lack of a plane bed configuration at low charge for sand size material indicates that the bed material properties which were eliminated by Cooper may play an important role in determining some phase boundaries.

The difficulty encountered in distinguishing between ripples and dunes may indicate that, in fact, there is no distinction between the two configurations in the experimental range of h/D. However, as there is also an imperceptible difference in resistance to flow and sediment transport, perhaps there is no need to distinguish between these bed forms in the experimental range of h/D. If such a distinction were necessary, an adjustment of the Cooper ripple-dune boundary (as indicated in Figure 6-2) might be useful.

6-2 Recommendations

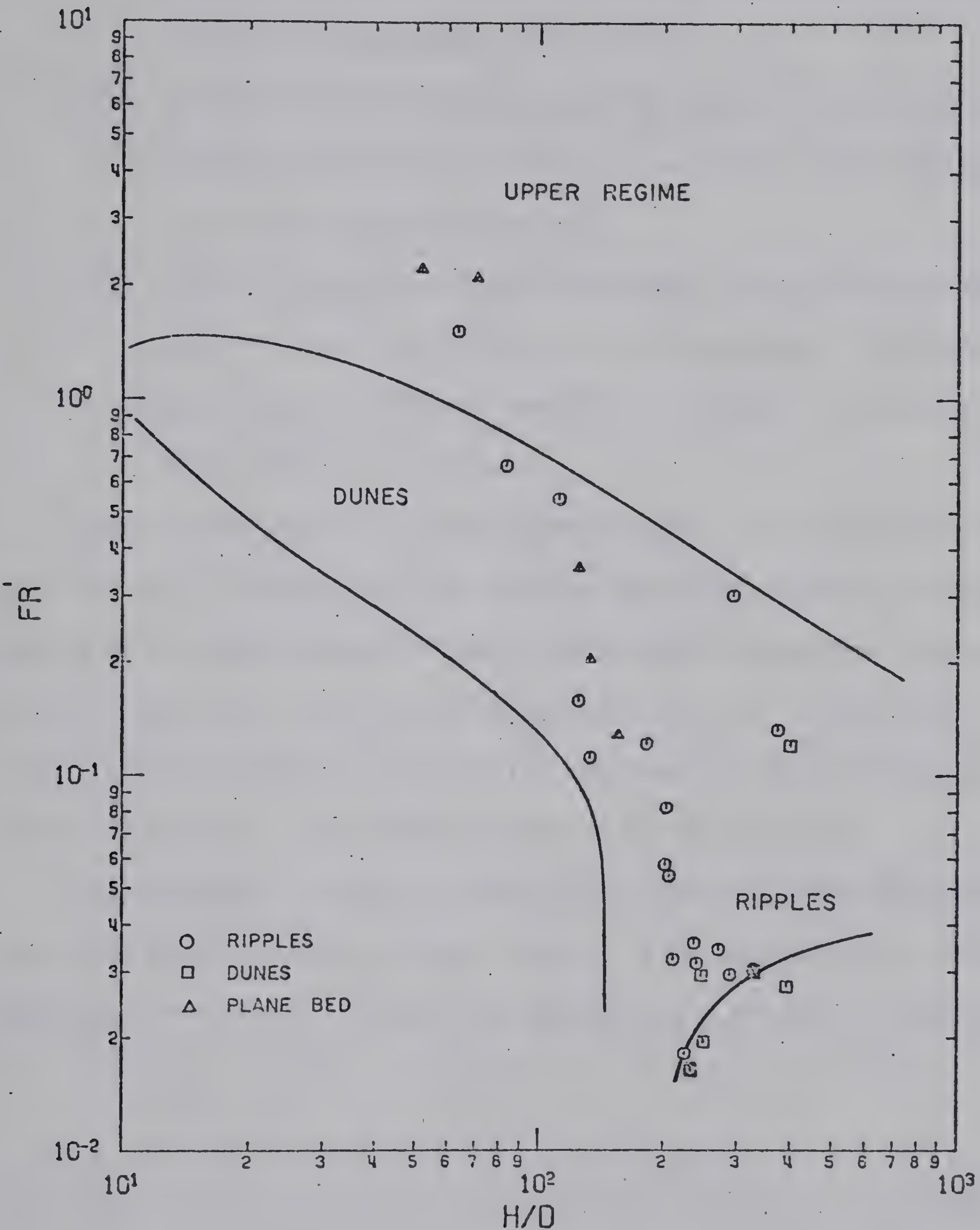
As this has been an experimental study, the recommendations deal mostly with proposed modifications to the apparatus. These changes are suggested in light of the experience gained in operating the existing system:

(1) Cooling coils could be added to the return line to reduce evaporation or an automatic system could be developed (perhaps by means of a float arrangement) to control the



BED CONFIGURATION - FR' VS H/D

FIGURE 6-1.



BED CONFIGURATION - FR' VS H/D

FIGURE 6-2.

quantity of water in the flume.

(2) The flume bed and walls could be extended beyond the inlet to the sand pump in order to provide a damping effect to any sudden adjustments in Q, S or h.

(3) A better means should be found for obtaining bed form dimensions (an optical bed plotter is currently under development at the University of Alberta).

(4) A pitot tube could be used to obtain more precise velocity profiles over the various bed configurations. This system would necessitate slow backflow to prevent its being plugged with sediment particles.

With regard to further experimental work, it is recommended that more efforts, in addition to the improved apparatus mentioned above, be applied to the determination of the relationship between bed form geometry and flow conditions. It is also recommended that the significance of bed material properties in determining the location of the plane bed (low charge) to ripple or dune phase boundaries be investigated.

Furthermore, in order to substantiate the existence of a zone of transition between dunes and upper regime, it is suggested that further testing be done with C constant and maintaining a uniform bed configuration.

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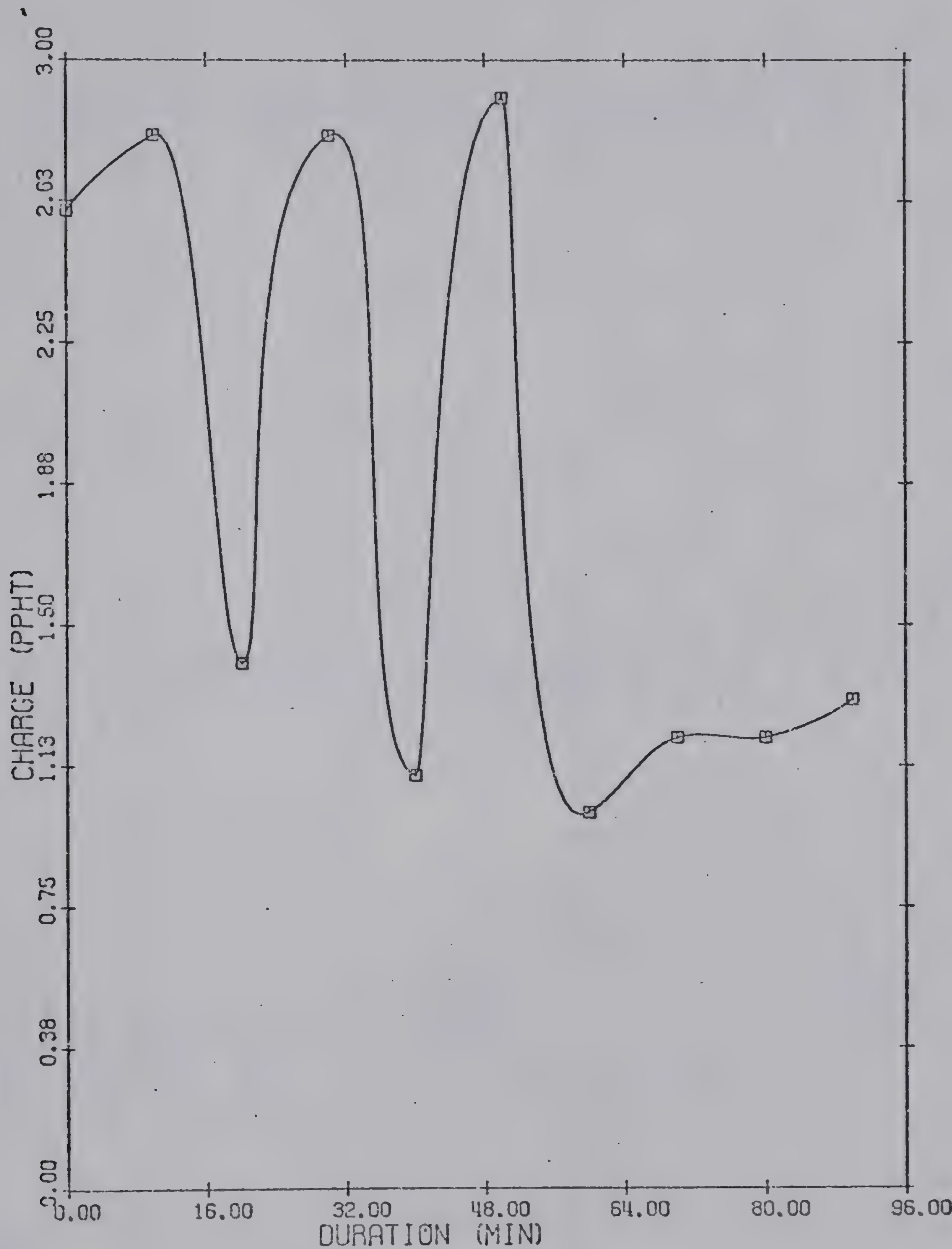
APPENDIX



PLOT OF TIME VARIATION OF C

FIGURE A-1.

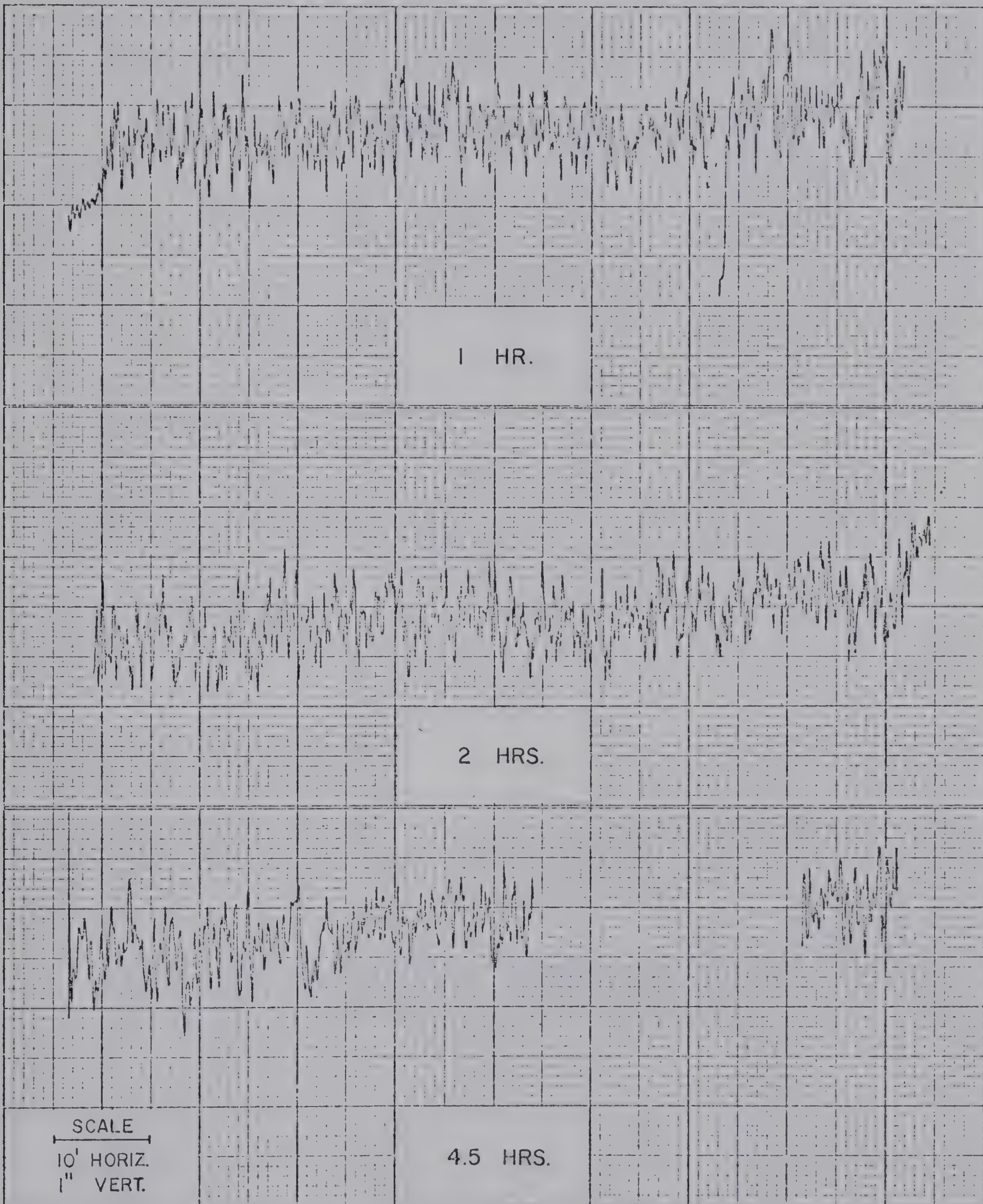


FIGURE A-2. PROFILES OF BED
t HOURS AFTER COMMENCEMENT

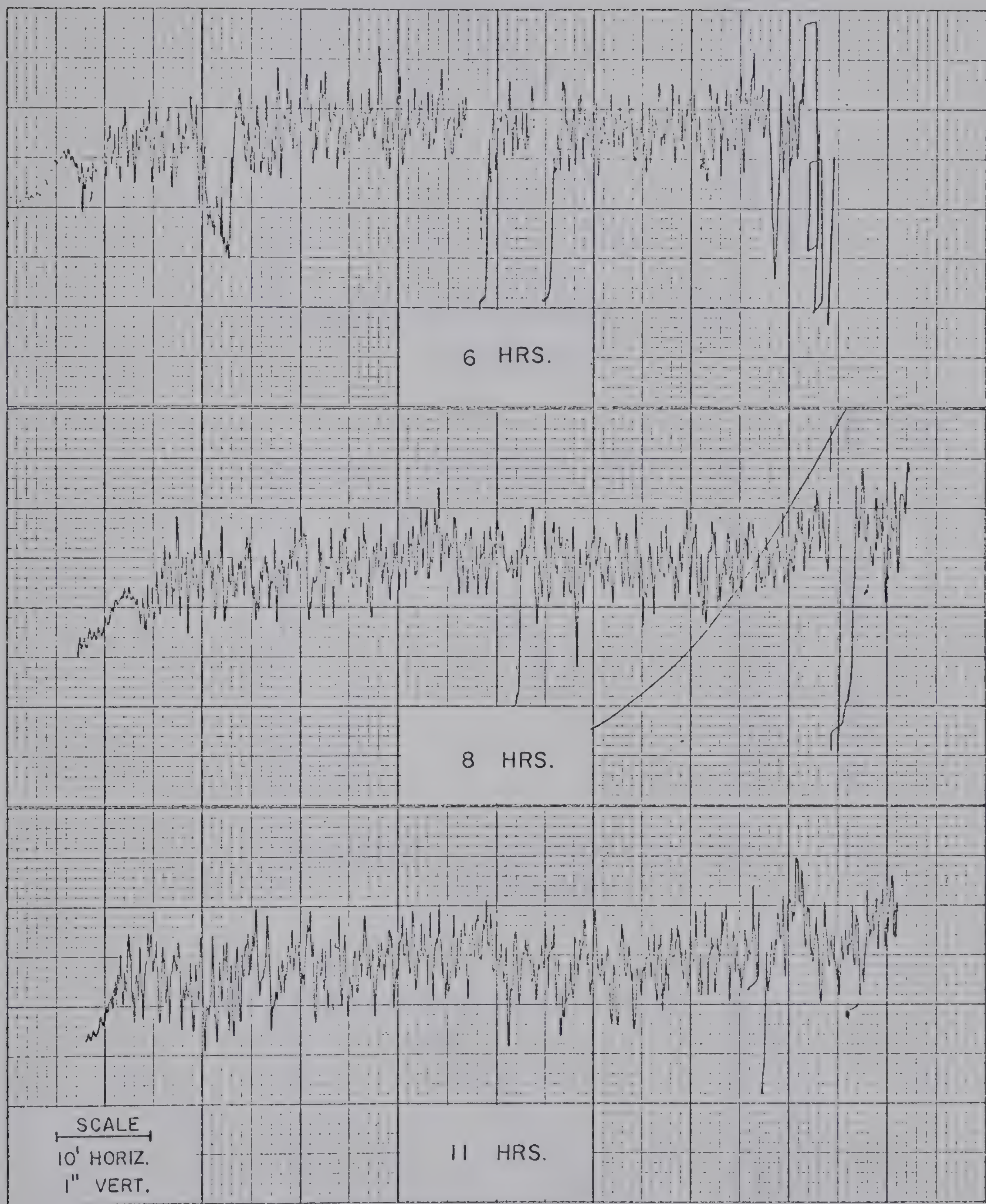
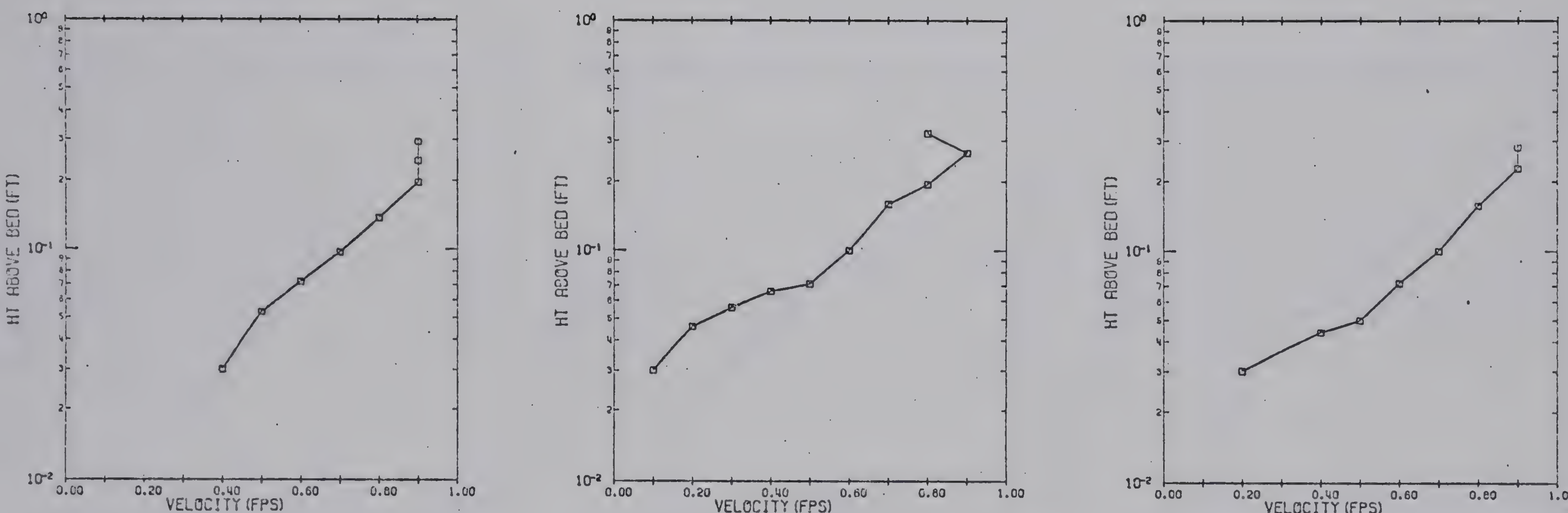
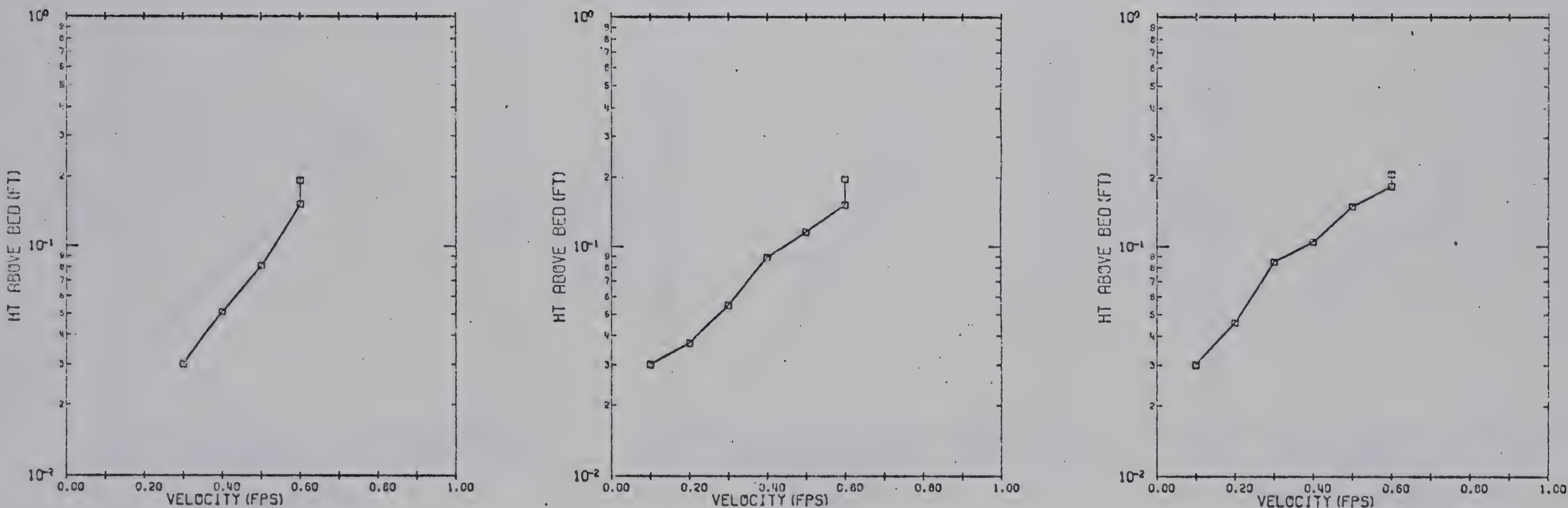


FIGURE A-3. PROFILES OF BED
t HOURS AFTER COMMENCEMENT



RUN 4 - LT. 3RD PT.   RUN 4 - C.L.   RUN 4 - RT. 3RD PT.

FIG. A-4. VELOCITY PROFILES — RUN 4

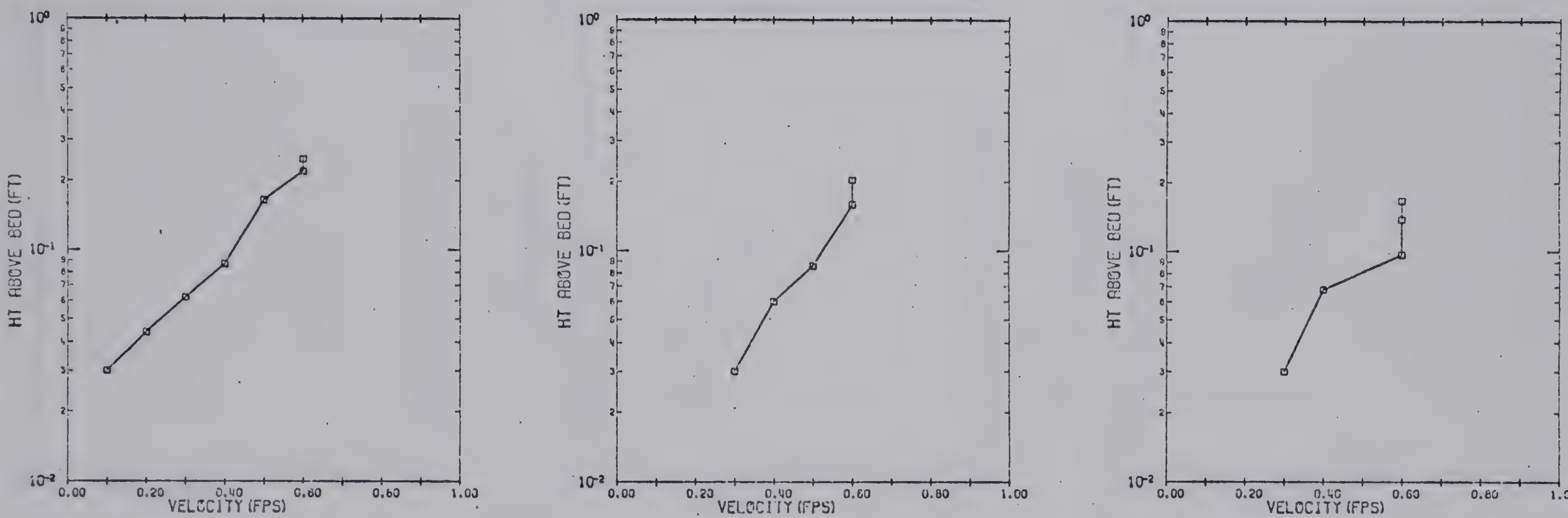


RUN 5 - LT. 3RD PT.

RUN 5 - C.L.

RUN 5 - RT. 3RD PT.

FIG. A-5. VELOCITY PROFILES - RUN 5

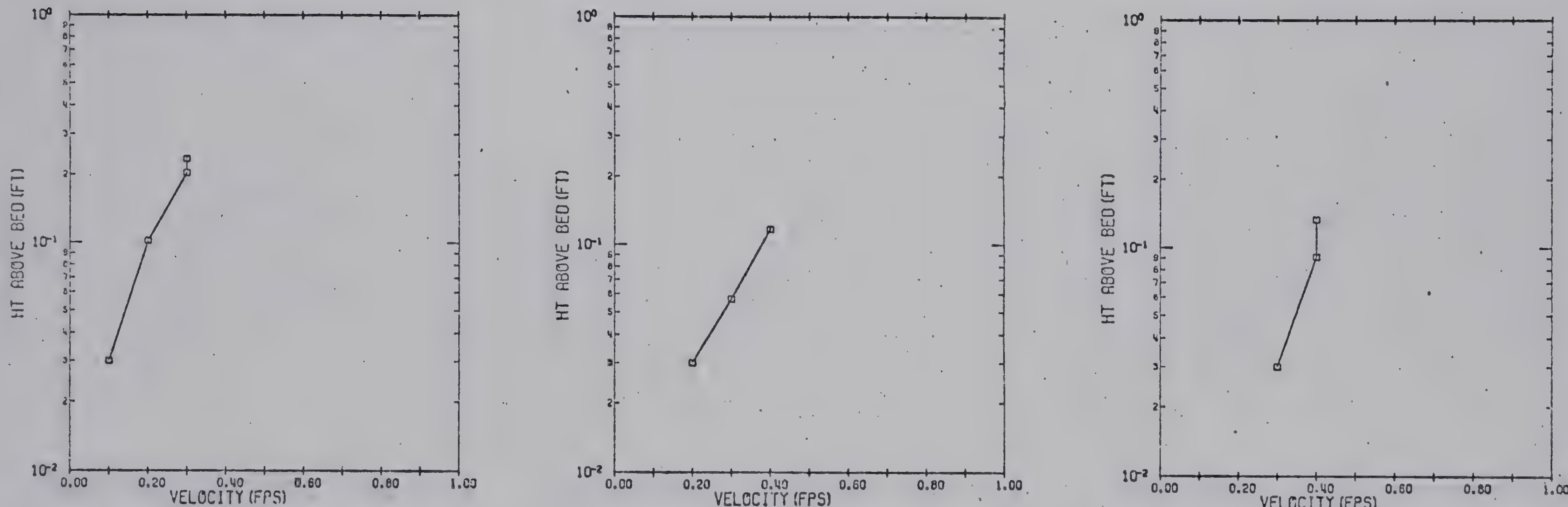


RUN 6 - LT. 3RD PT.

RUN 6 - C.L.

RUN 6 - RT. 3RD PT.

FIG. A-6. VELOCITY PROFILES — RUN 6

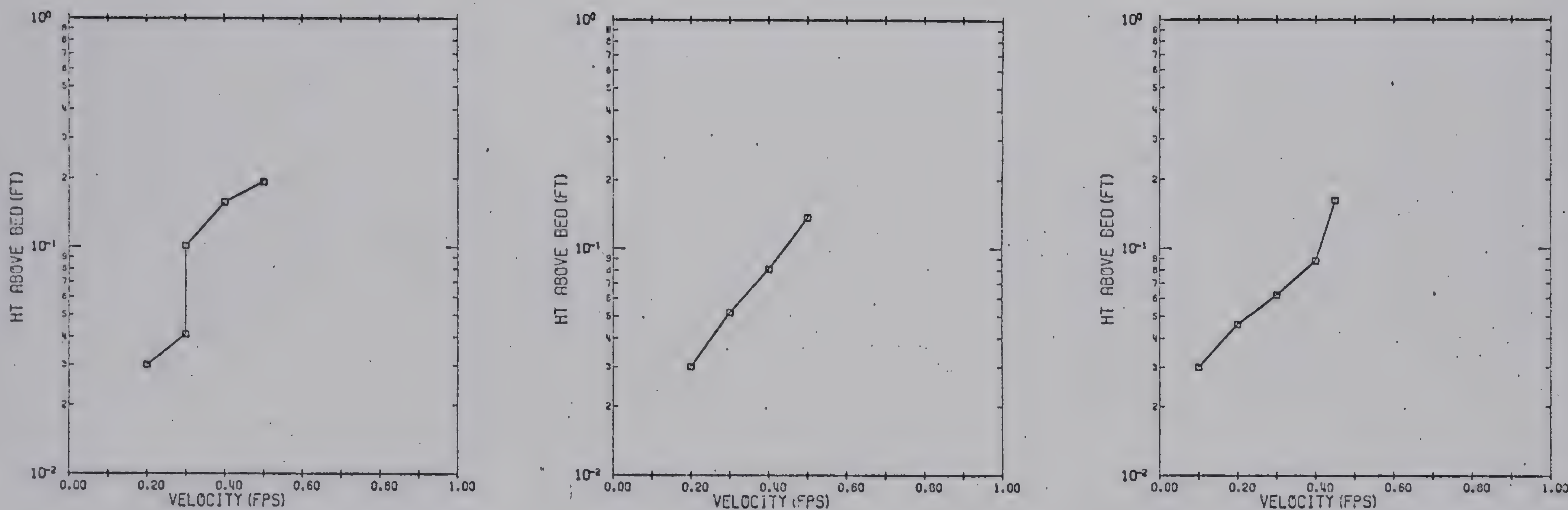


RUN 7 - LT. 3RD PT.

RUN 7 - C.L.

RUN 7 - RT. 3RD PT.

FIG. A-7. VELOCITY PROFILES — RUN 7

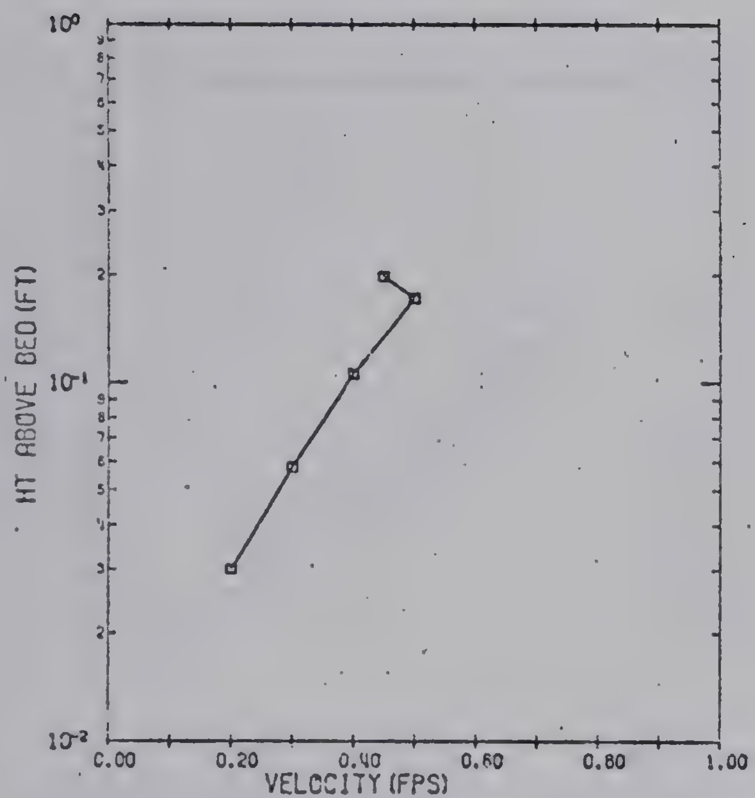


RUN 8 - LT. 3RD PT.

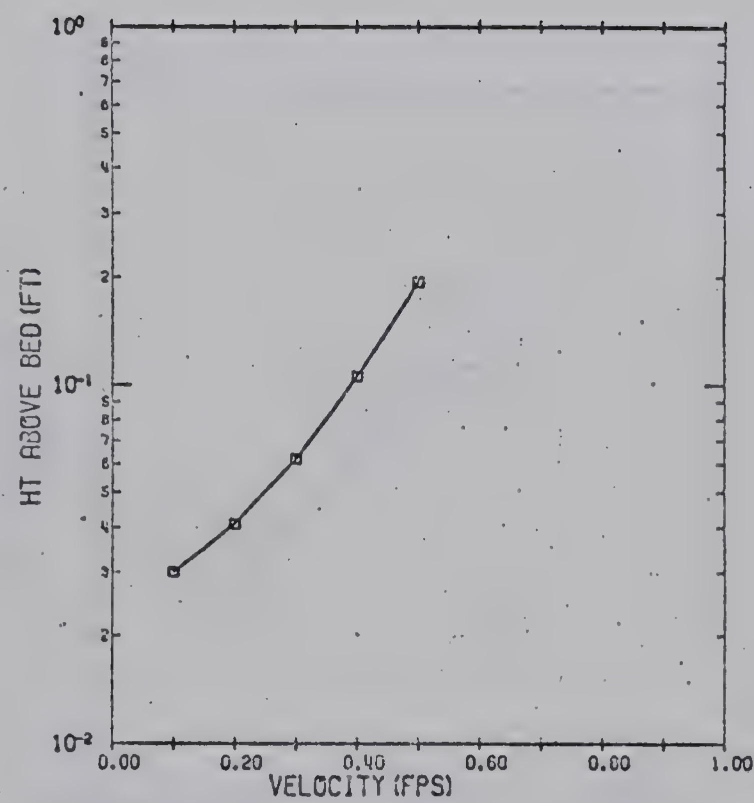
RUN 8 - C.L.

RUN 8 - RT. 3RD PT.

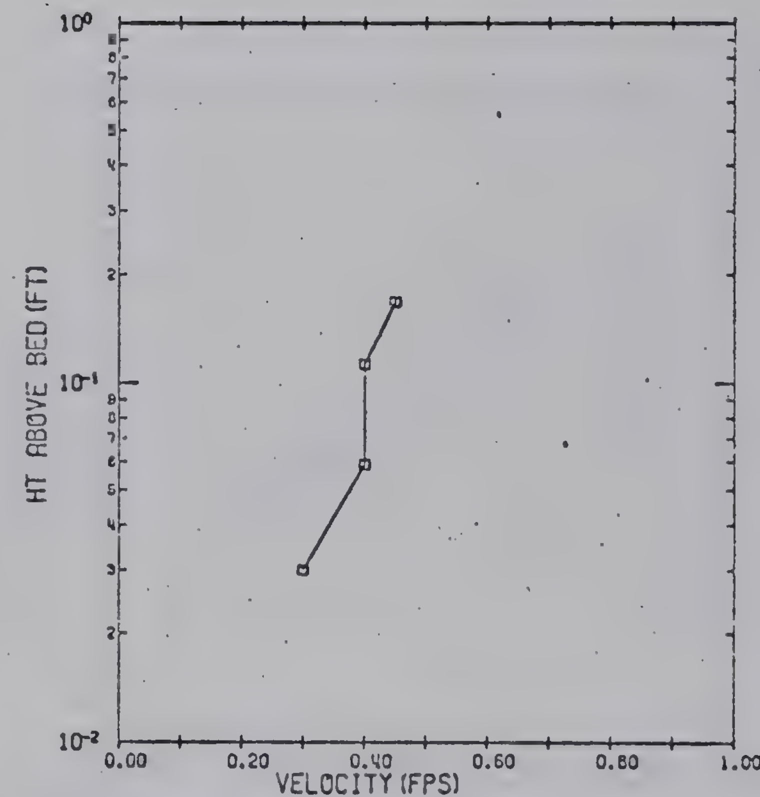
FIG. A-8. VELOCITY PROFILES — RUN 8



RUN 11 - LT. 3RD PT.

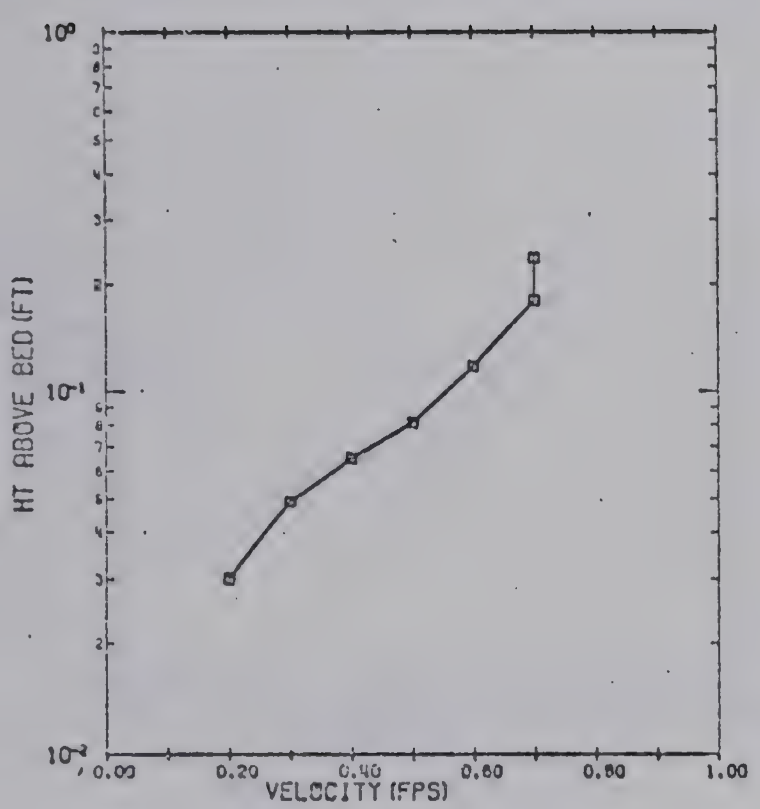


RUN 11 - C.L.

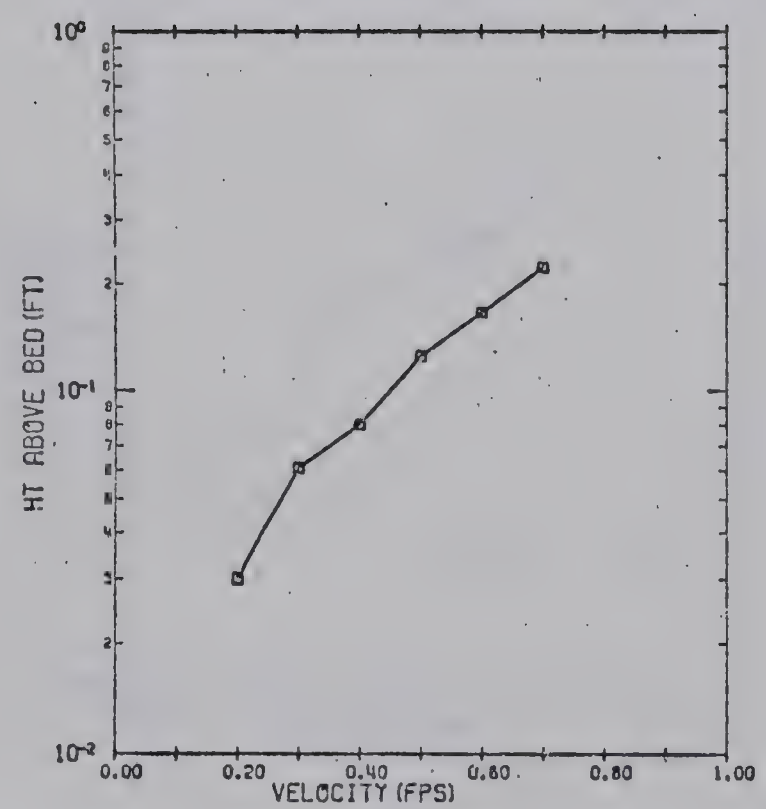


RUN 11 - RT. 3RD PT.

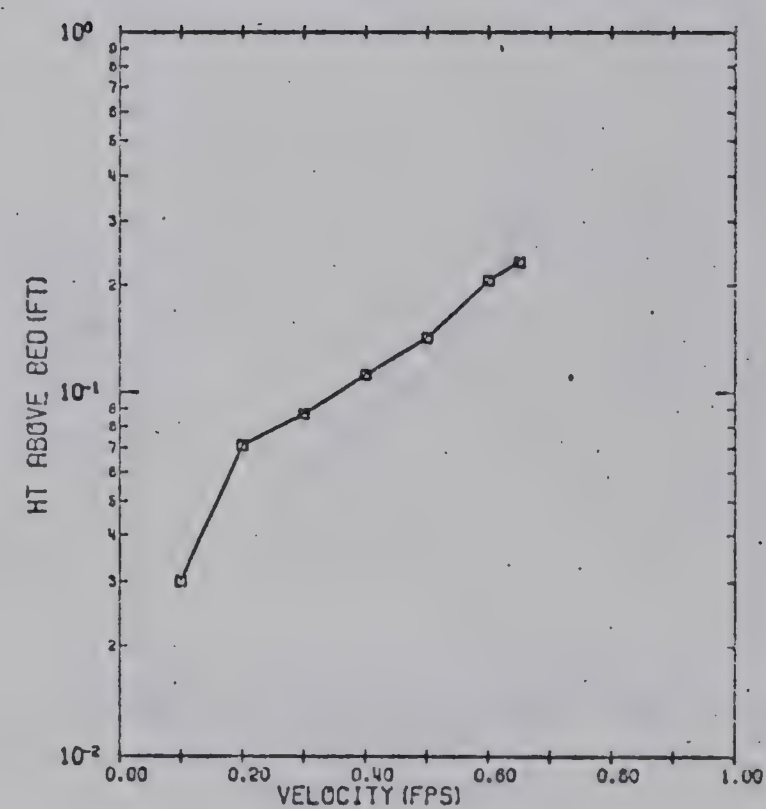
FIG. A-9. VELOCITY PROFILES — RUN II



RUN 12 - LT. 3RD PT.

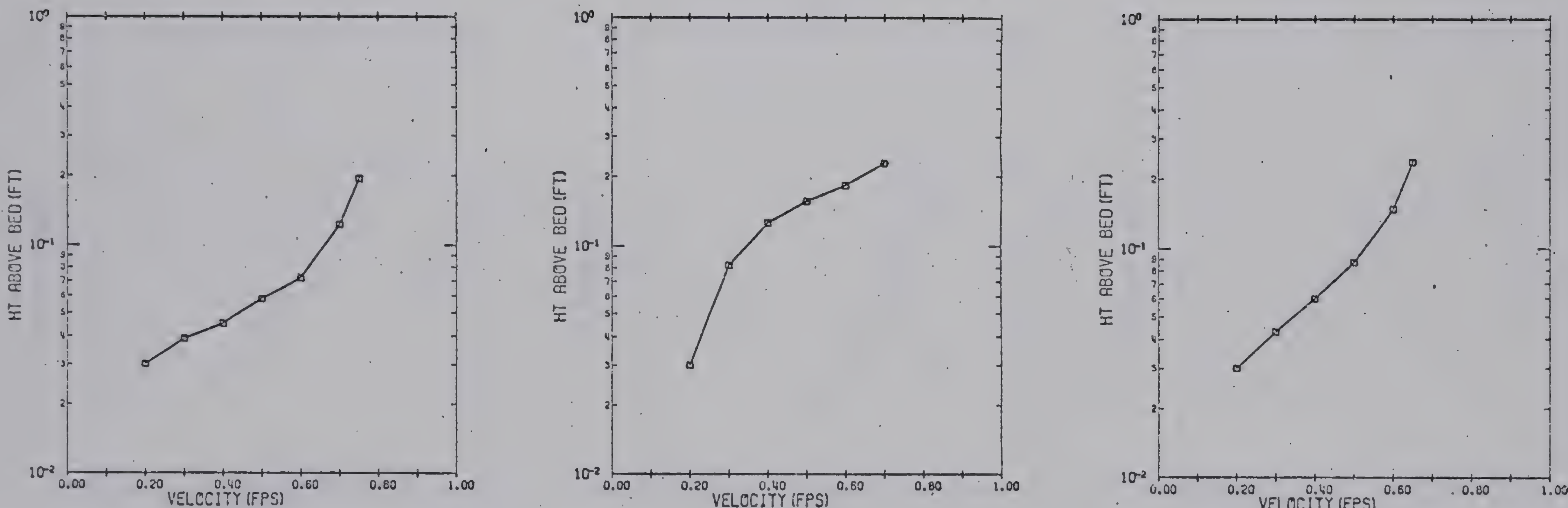


RUN 12 - C.L.



RUN 12 - RT. 3RD PT.

FIG. A-10. VELOCITY PROFILES - RUN 12

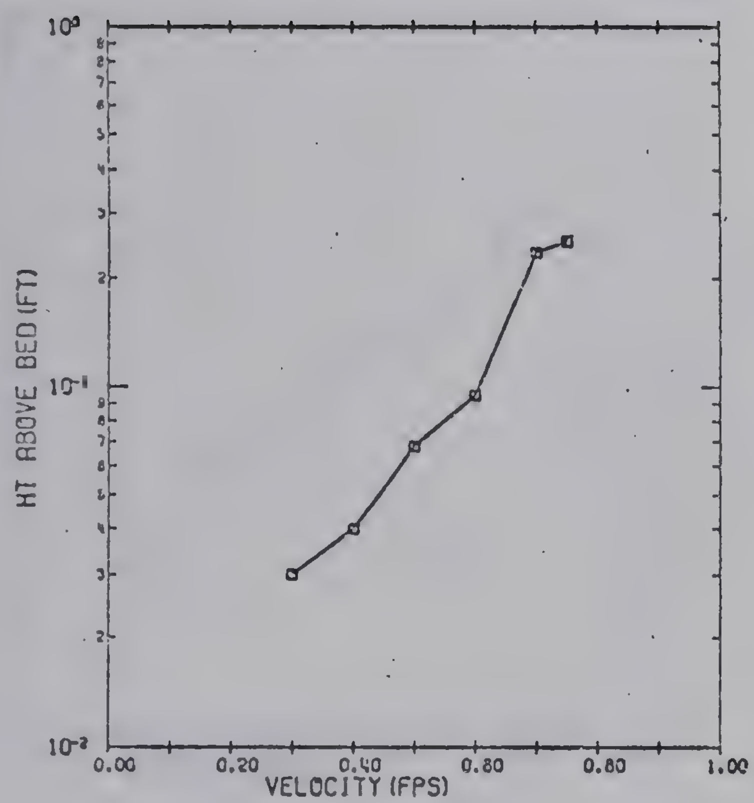


RUN 13 - LT. 3RD PT.

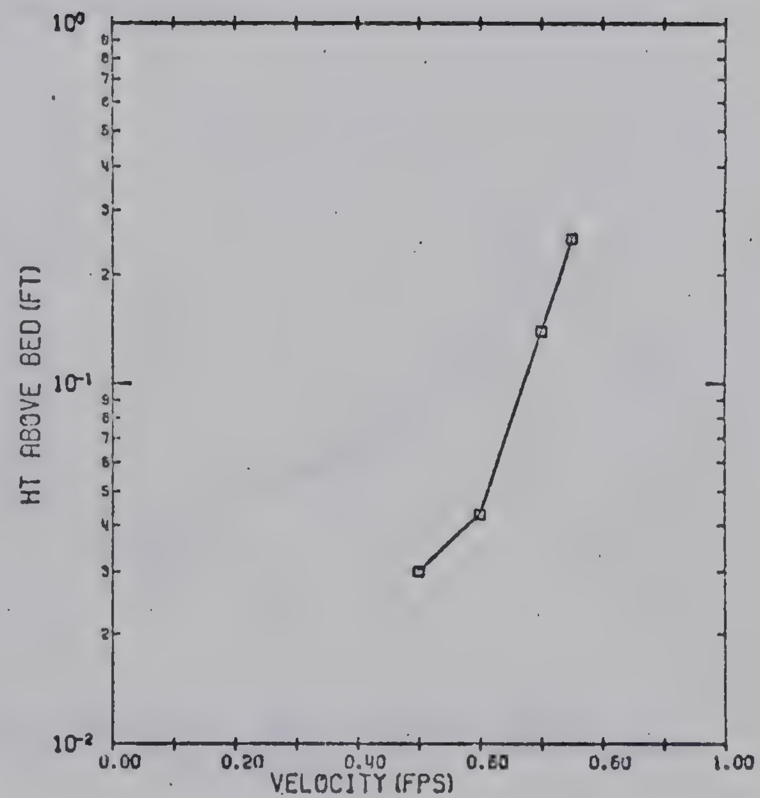
RUN 13 - C.L.

RUN 13 - RT. 3RD PT.

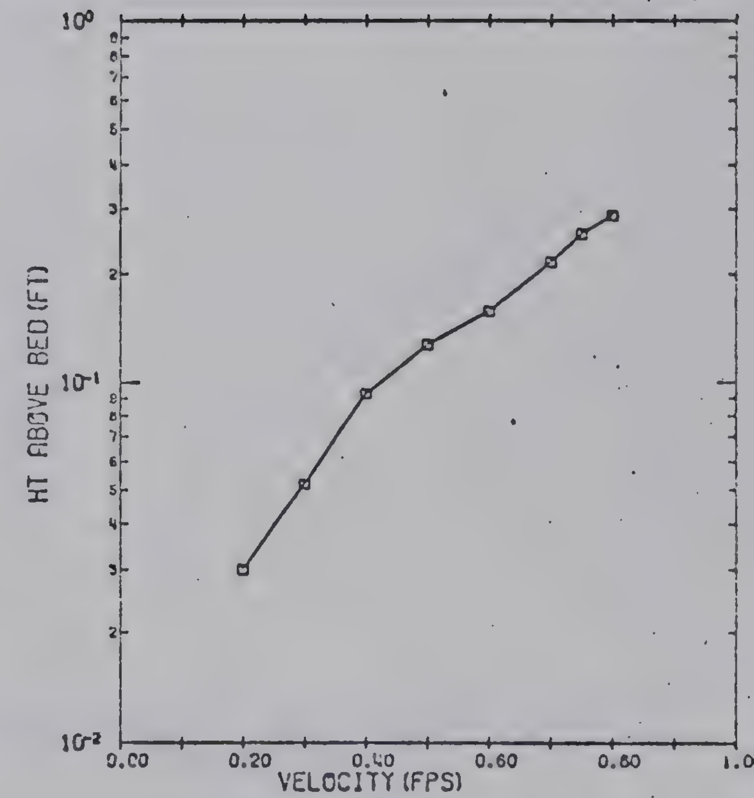
FIG. A-11. VELOCITY PROFILES — RUN 13



RUN 14 - LT. 3RD PT.

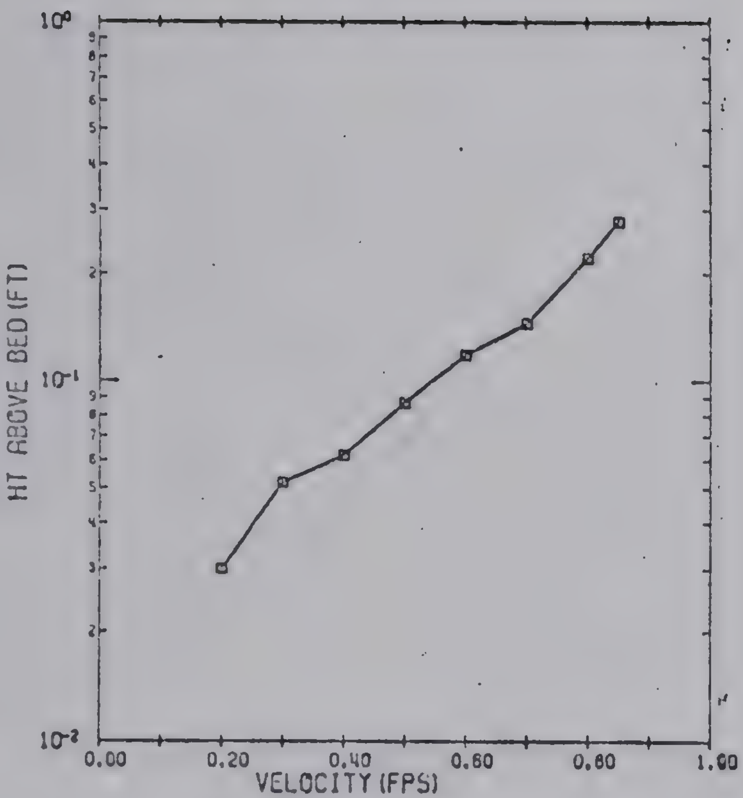


RUN 14 - C.L.

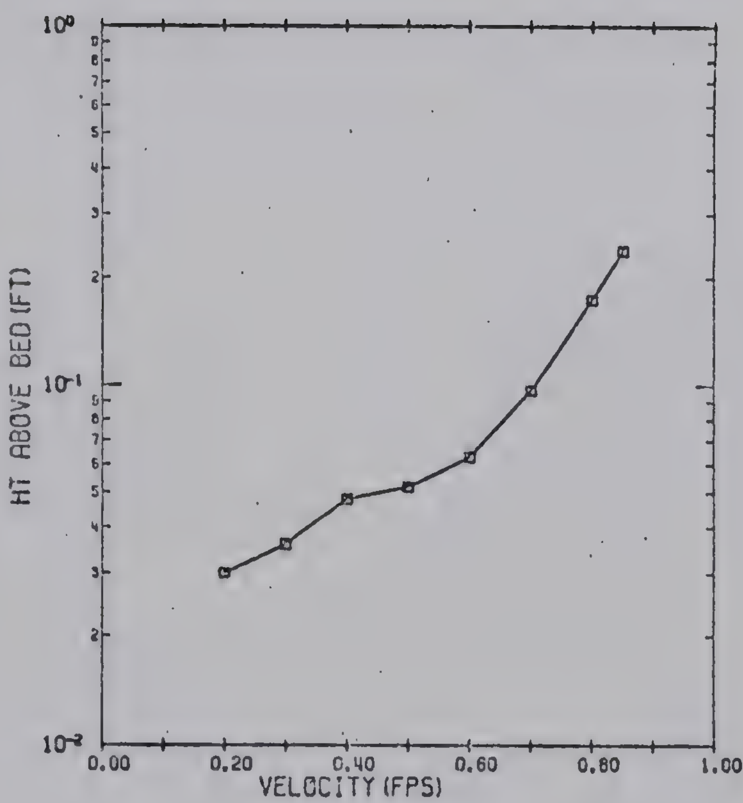


RUN 14 - RT. 3RD PT.

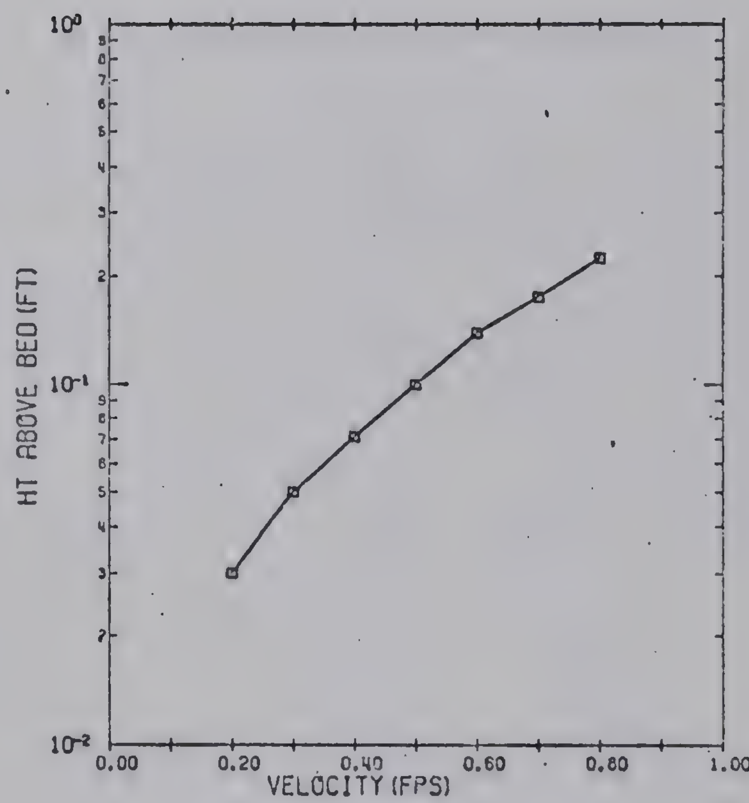
FIG. A-12. VELOCITY PROFILES — RUN 14



RUN 16 - LT. 3RD PT.

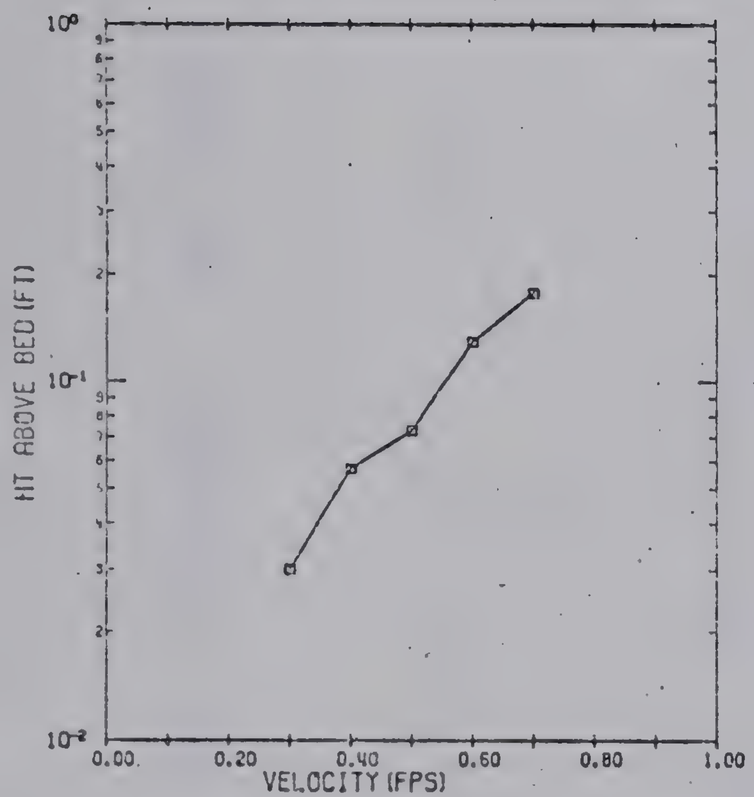


RUN 16 - C.L.

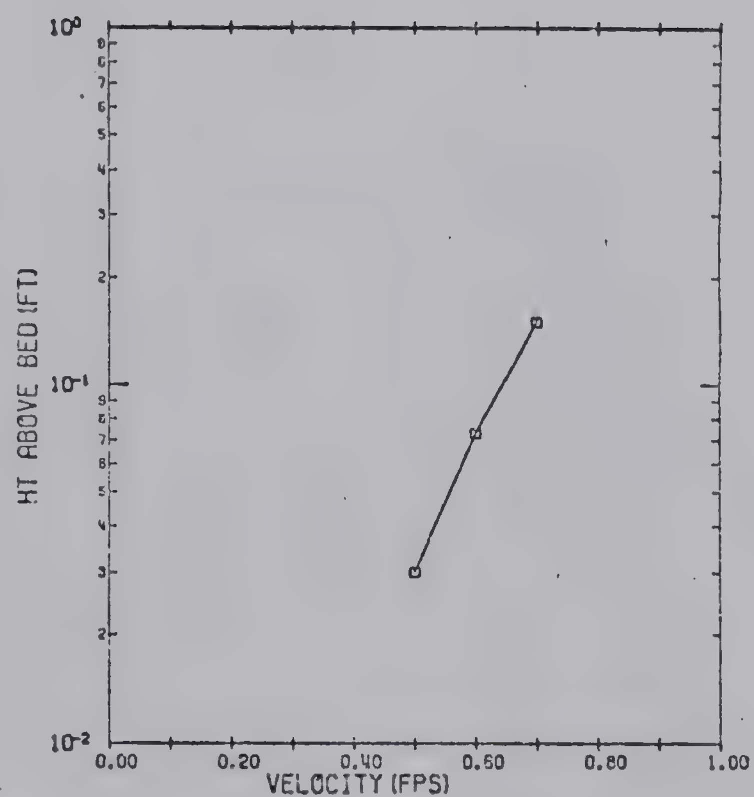


RUN 16 - RT. 3RD PT.

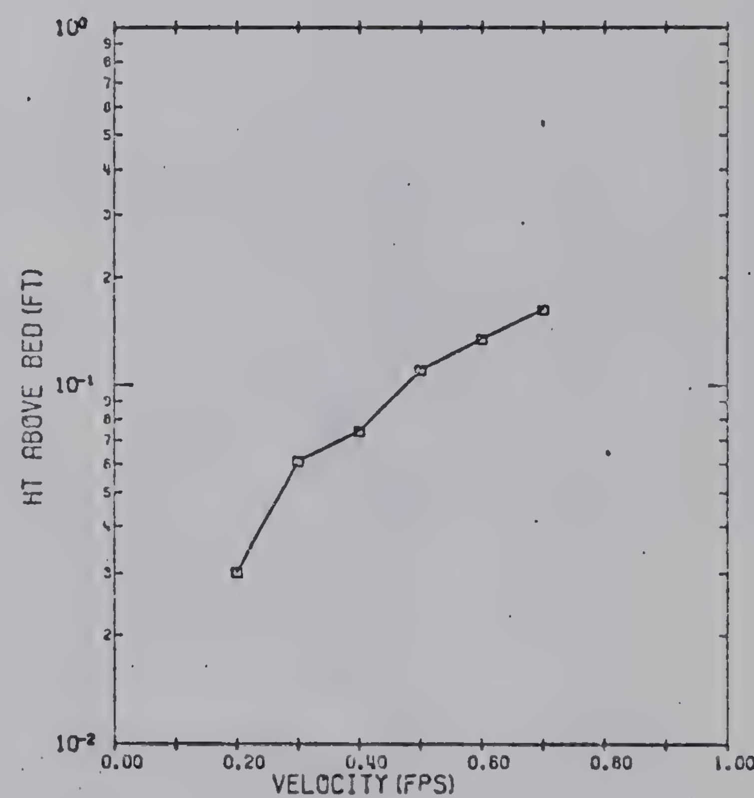
FIG. A-13. VELOCITY PROFILES —RUN 16



RUN 17 - LT. 3RD PT.



RUN 17 - C.L.



RUN 17 - RT. 3RD PT.

FIG. A-14. VELOCITY PROFILES – RUN 17

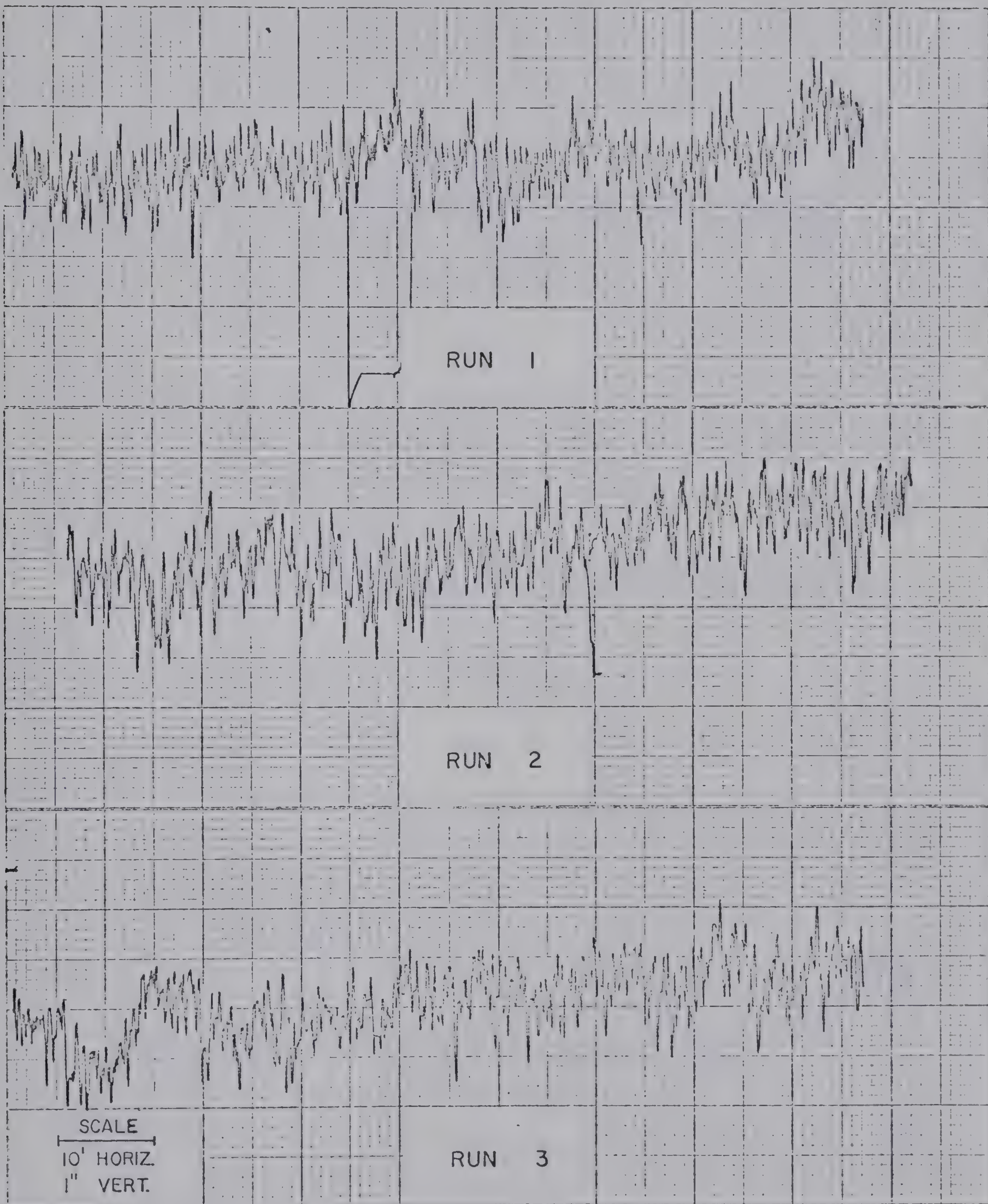


FIGURE A-15. PROFILES OF BED

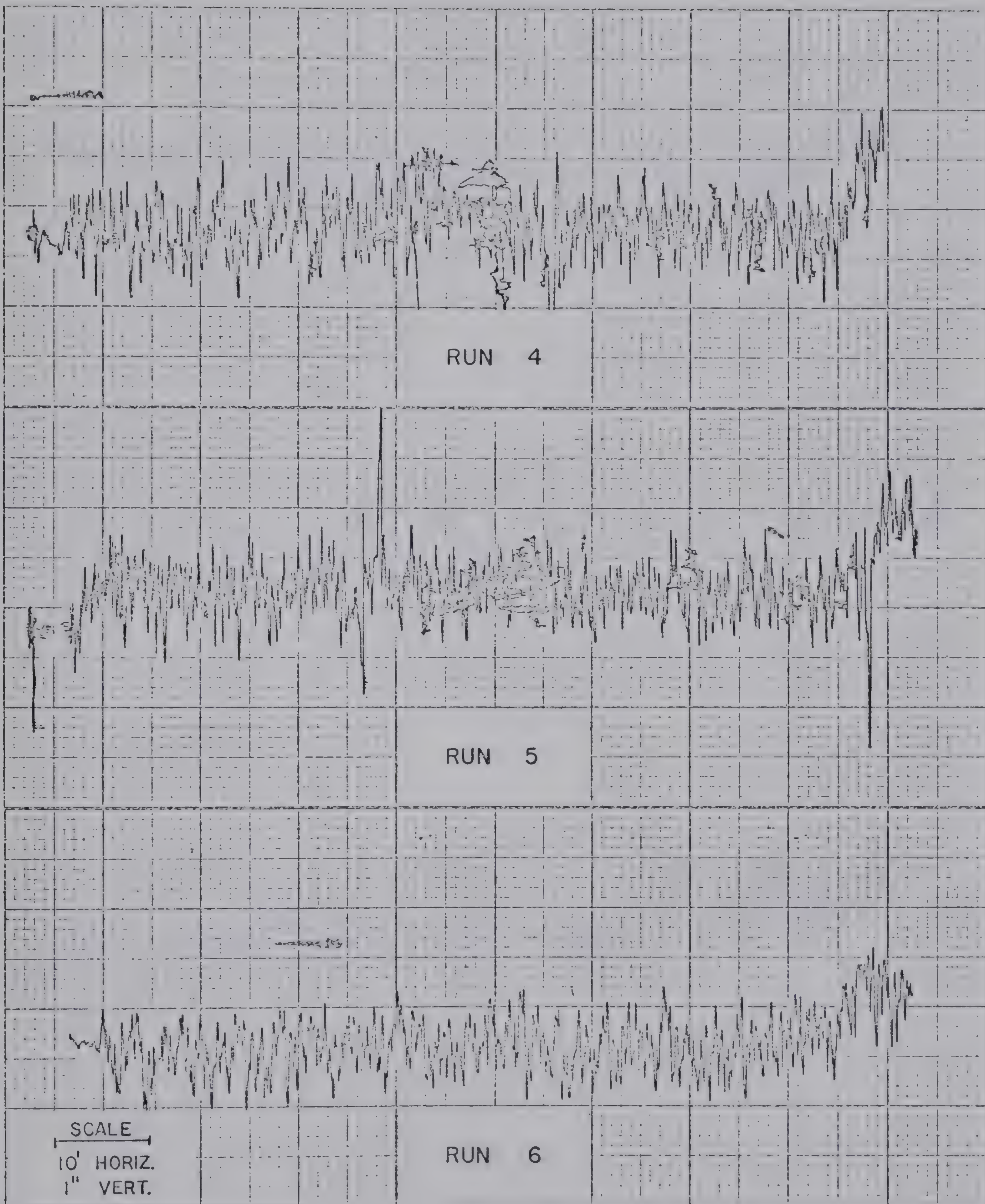


FIGURE A-16. PROFILES OF BED

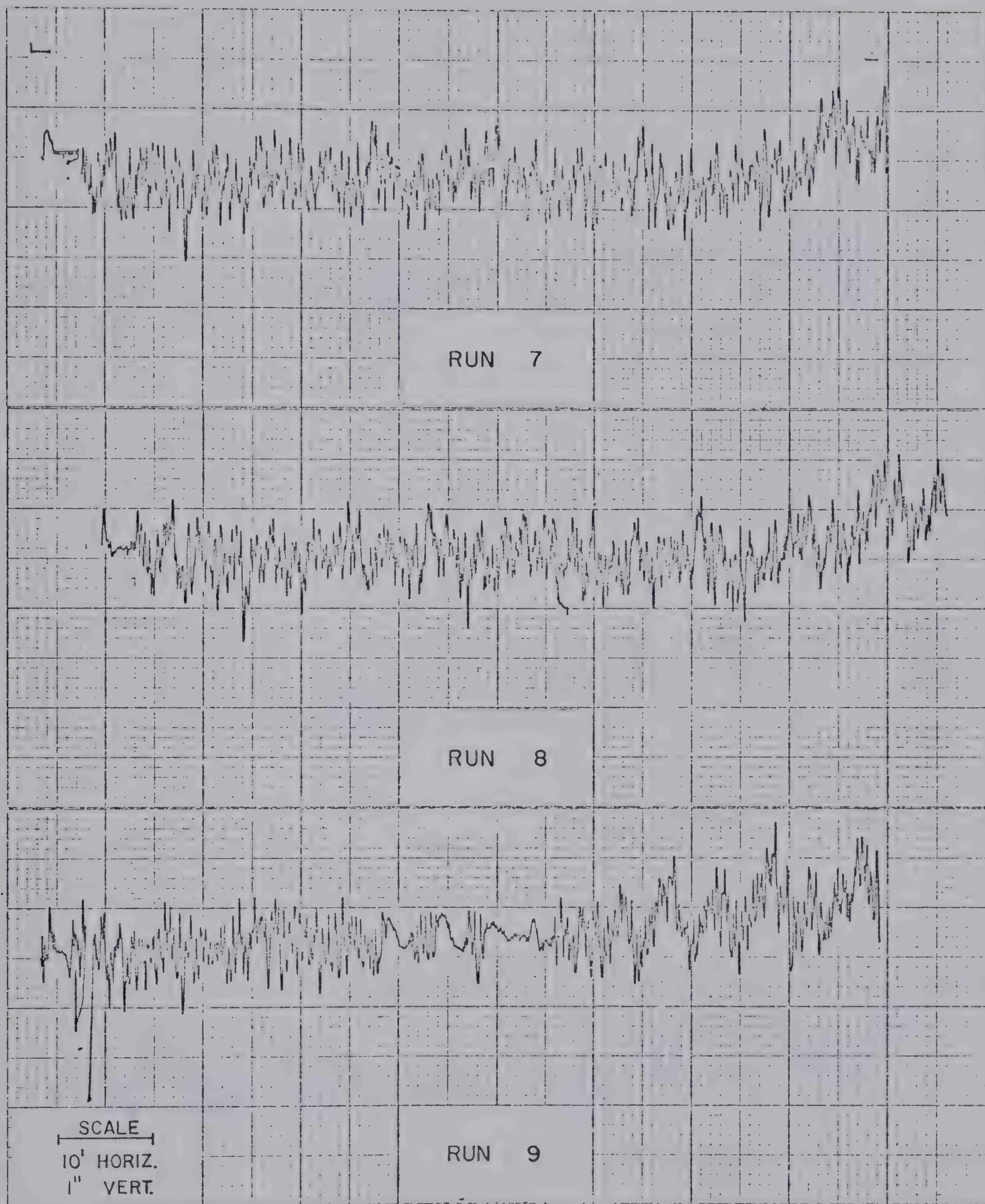


FIGURE A-1.7. PROFILES OF BED

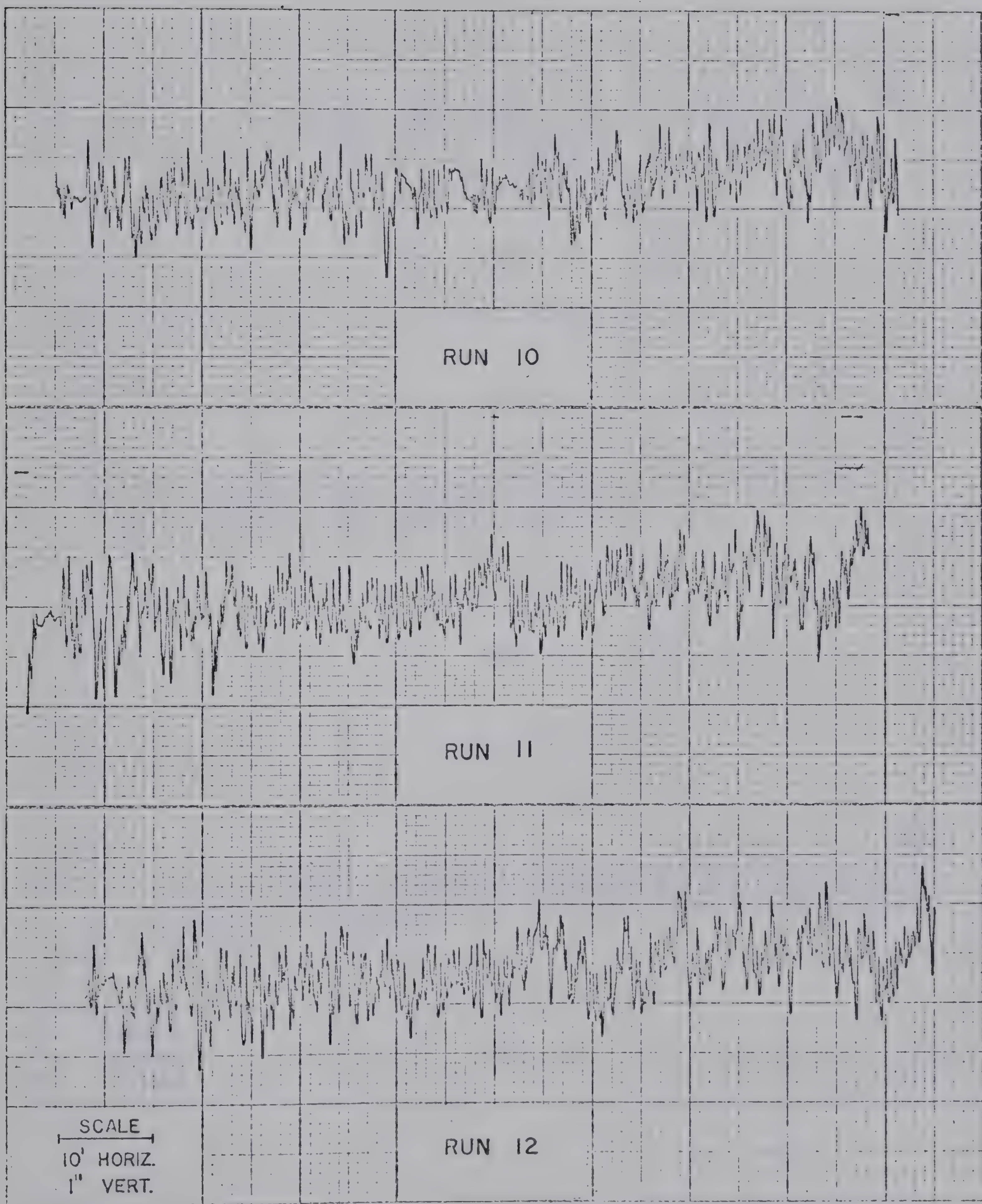


FIGURE A-18 PROFILES OF BED

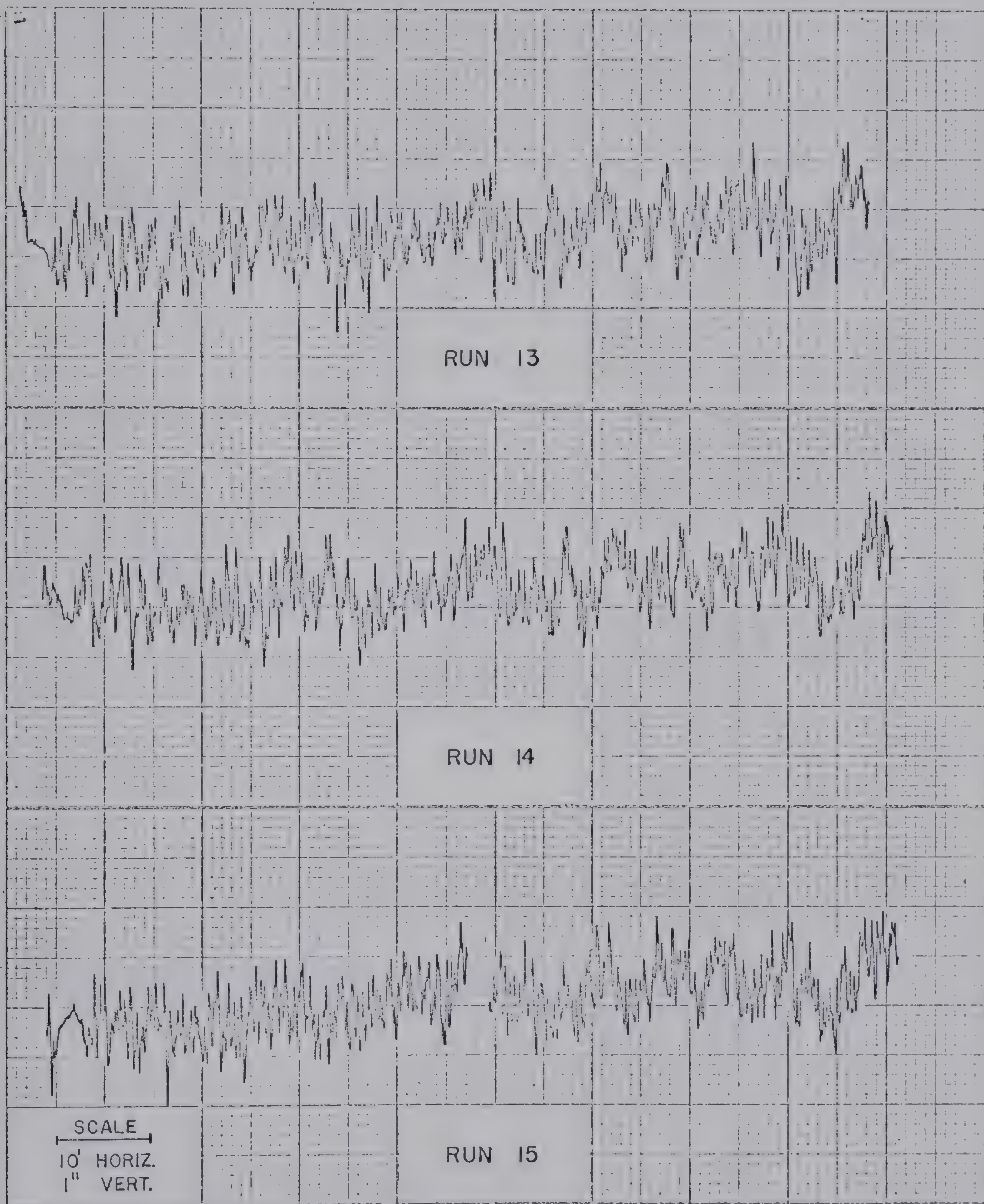


FIGURE A-19. PROFILES OF BED

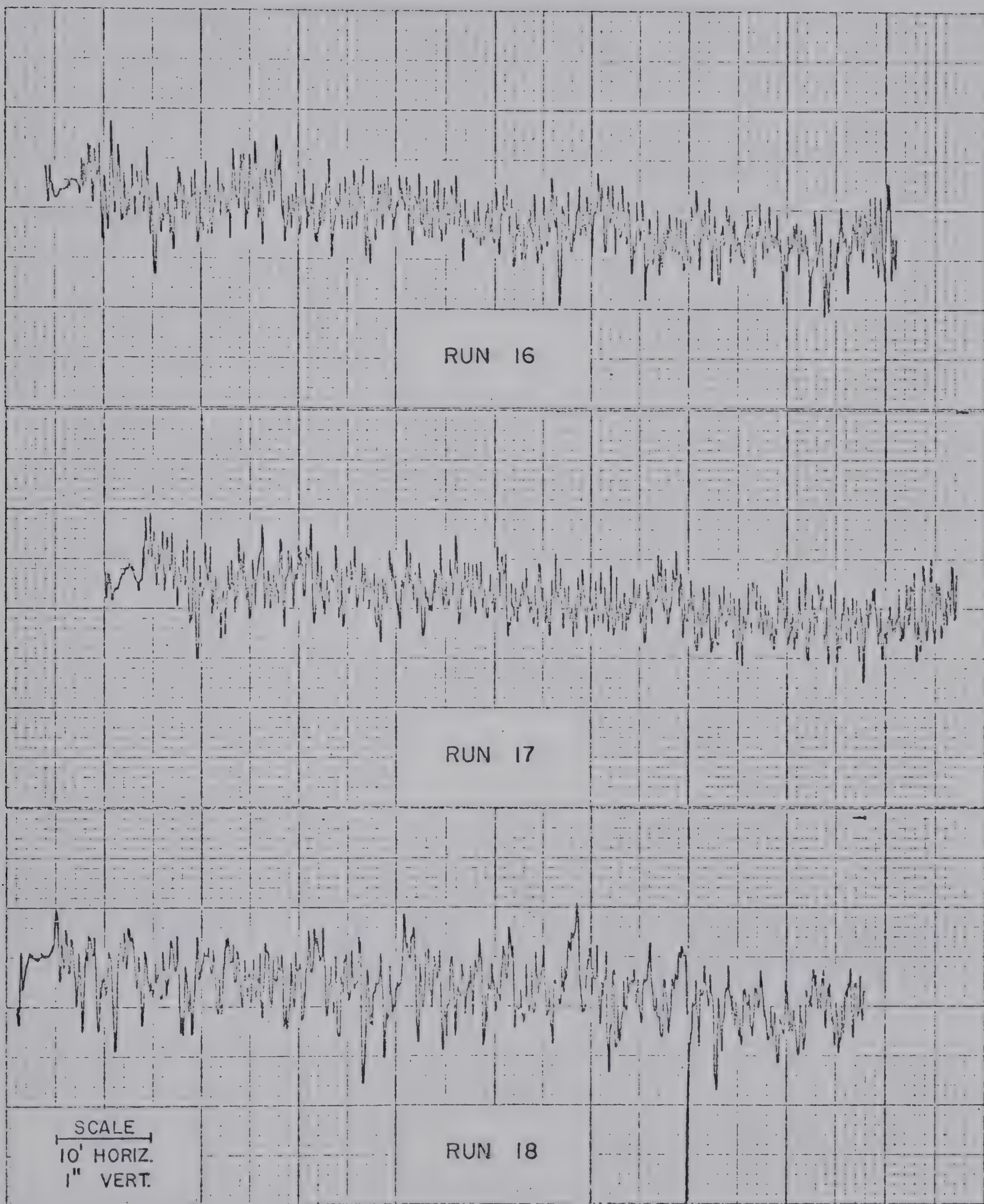


FIGURE A-20. PROFILES OF BED

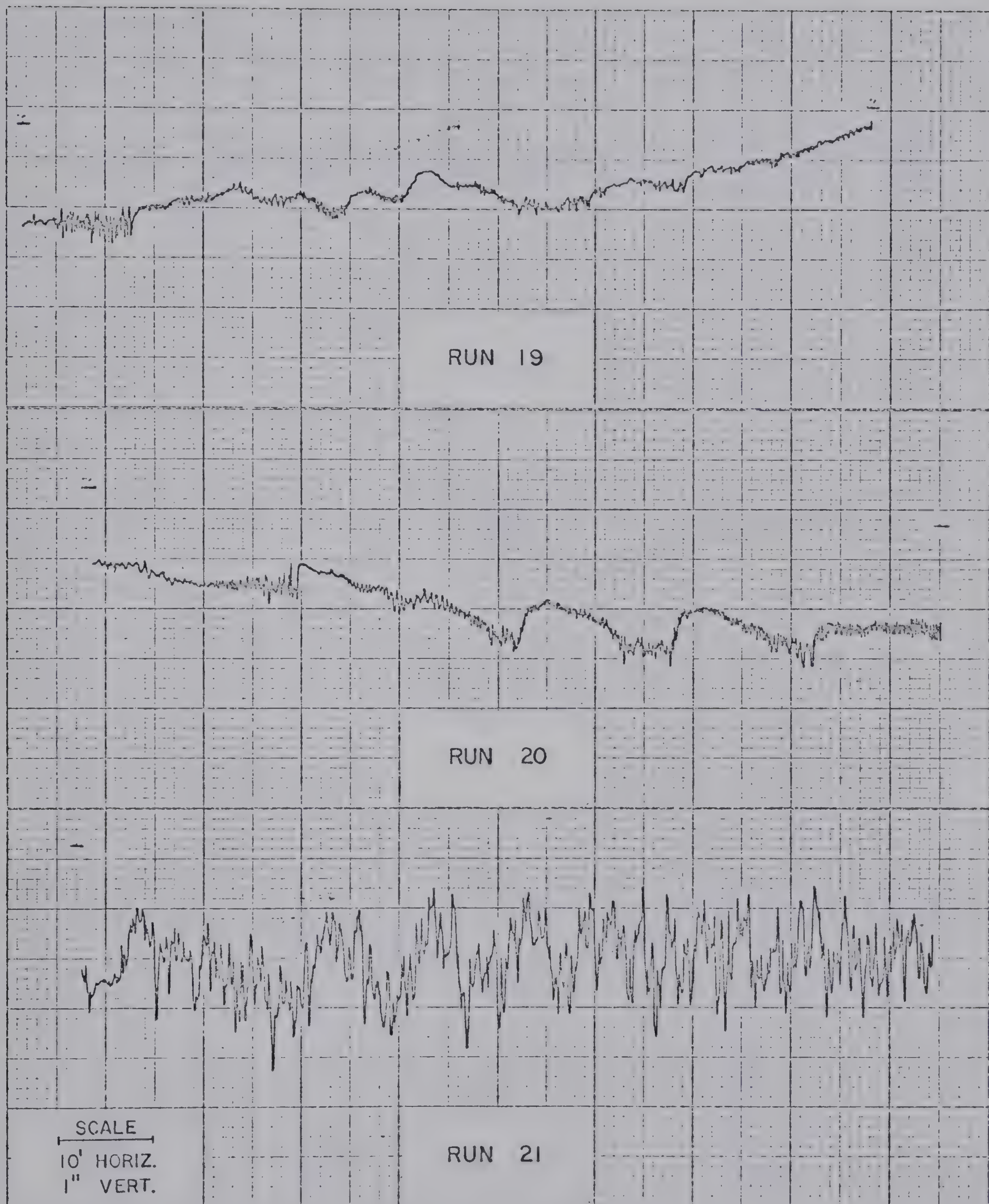


FIGURE A-21. PROFILES OF BED

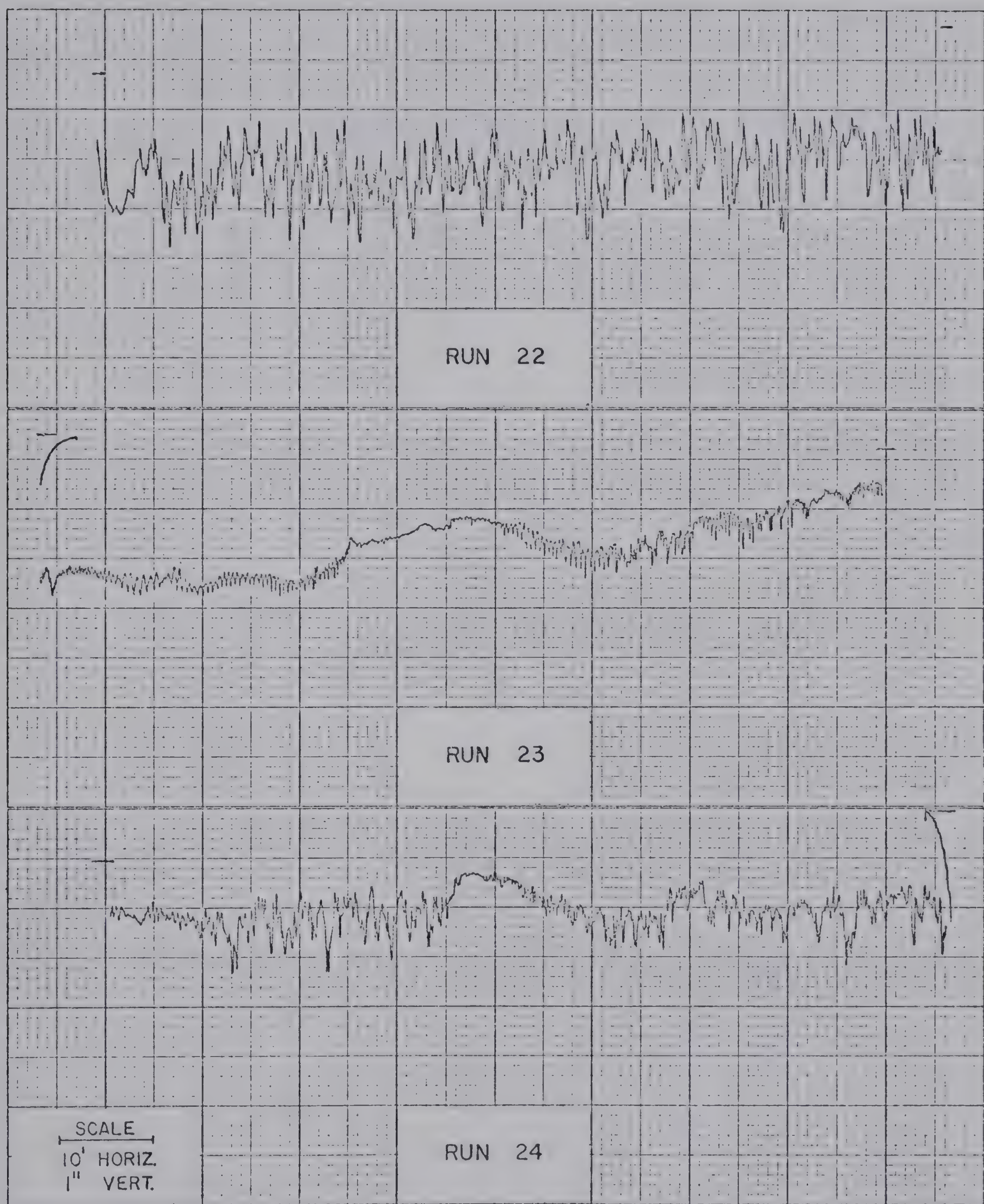
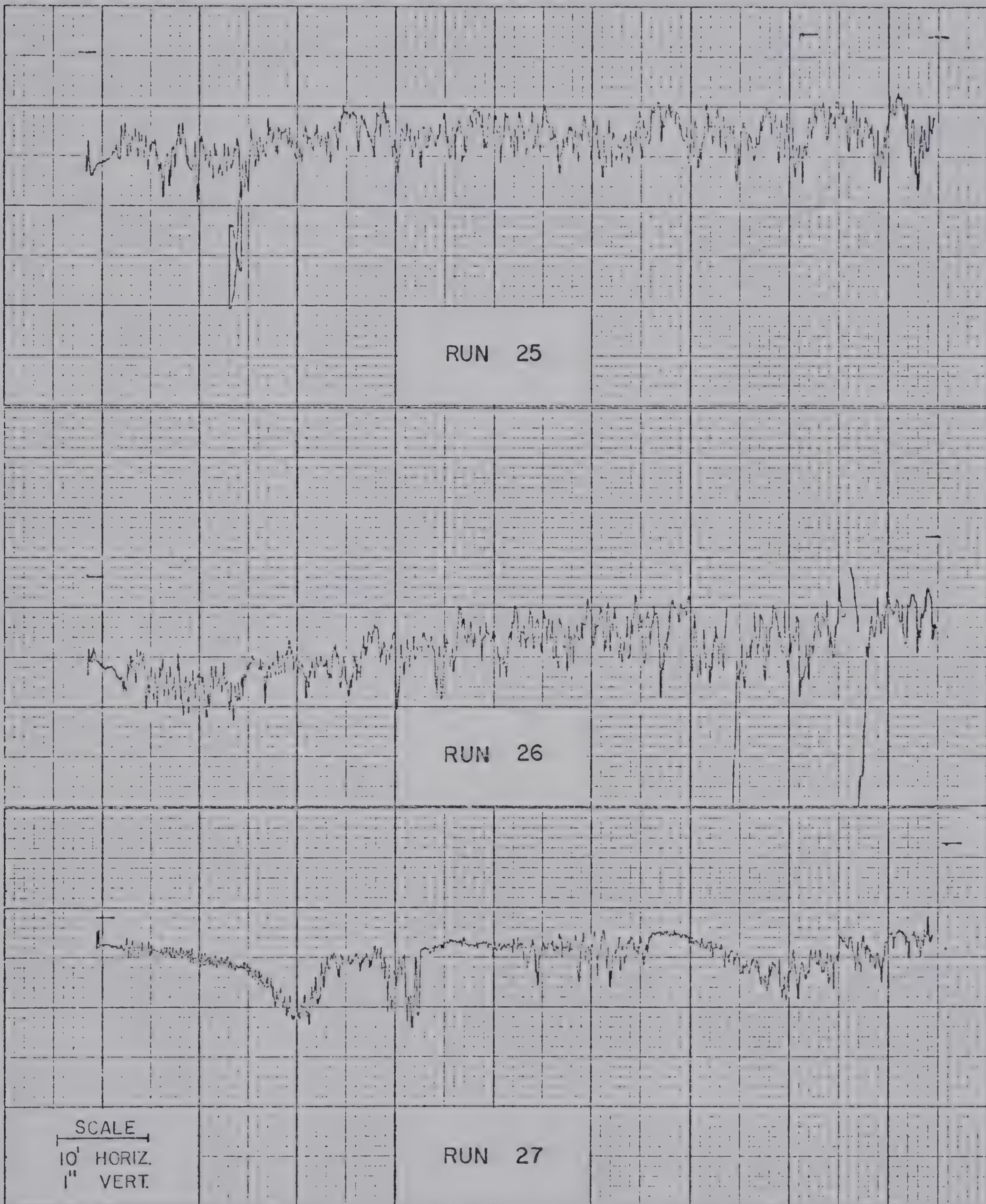


FIGURE A-22. PROFILES OF BED



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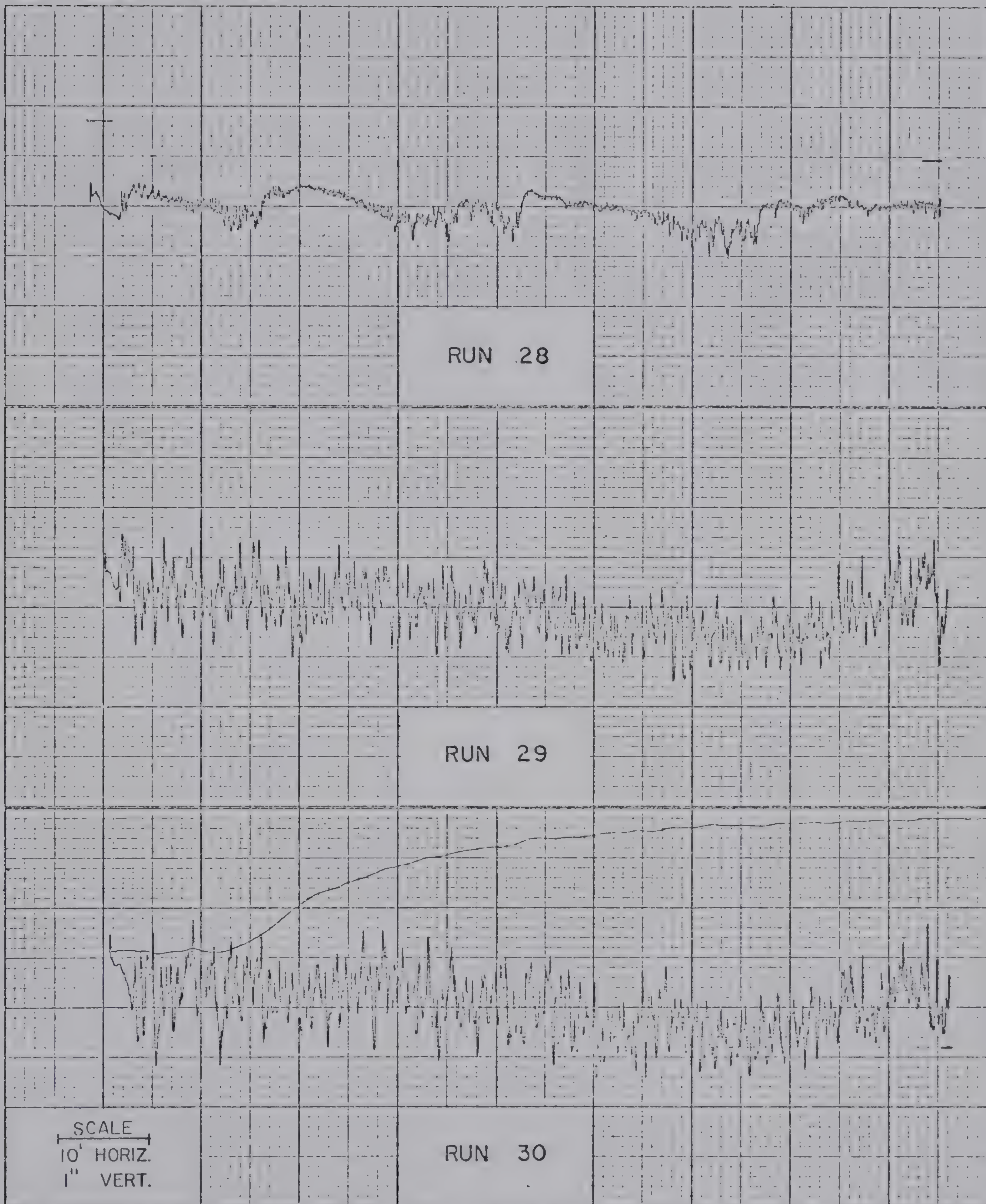

FIGURE A-24. PROFILES OF BED

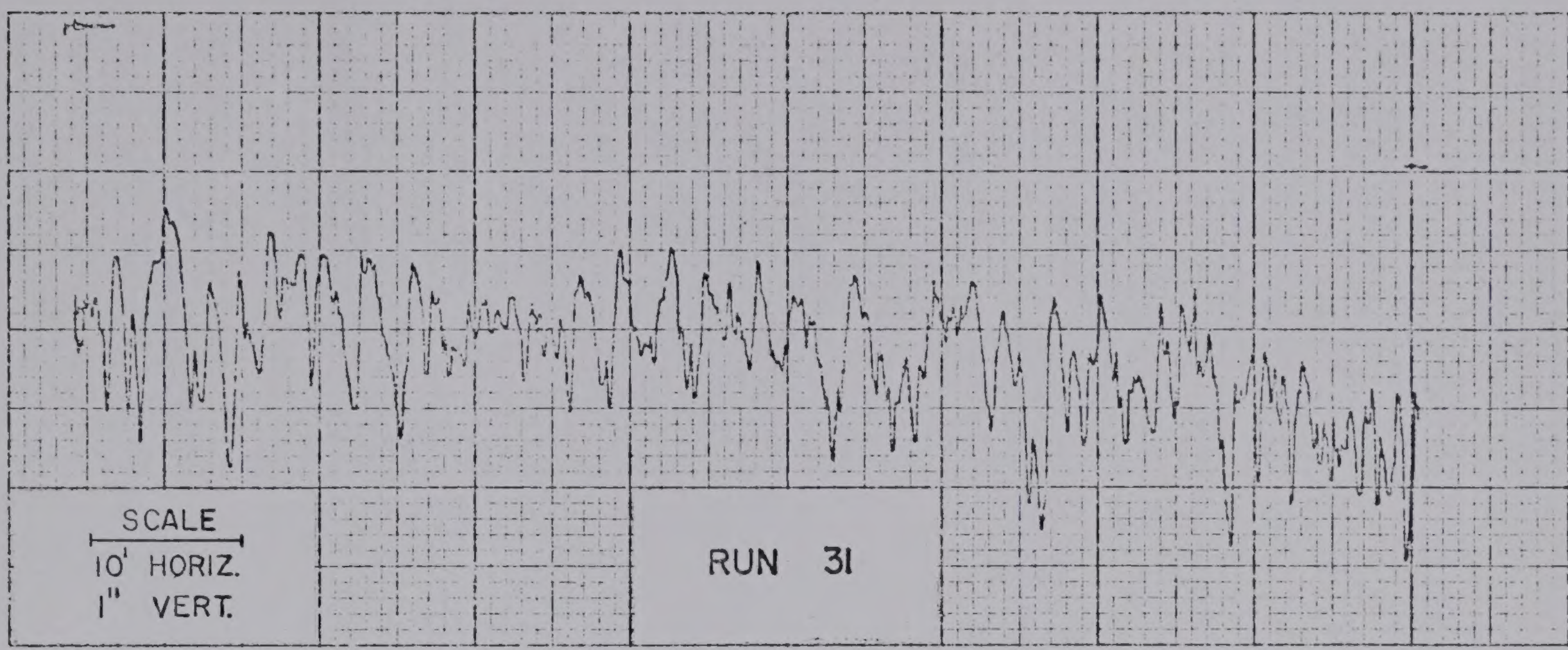

FIGURE A-25. PROFILES OF BED